Kaunas University of Technology

Faculty of Mechanical Engineering and Design

Development of Automated Adhesive Dispensing System Based on 3D Printer Platform

Master’s Final Degree Project

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Kaunas, 2026

Kaunas University of Technology

Faculty of Mechanical Engineering and Design

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Mechatronics (6211EX017)

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Task of the Master's Final Degree Project

Given to the student – Mantas Mačerinskas

1. Title of the Project

Development of Automated Adhesive Dispensing System Based on 3D Printer Platform

(In English)

Automatinės klijų dozavimo sistemos, pagrįstos 3D spausdintuvo platforma, kūrimas

(In Lithuanian)

2. Aim and Tasks of the Project

Aim: to develop a reliable automated glue dispensing system based on a 3D printer platform suitable for use in industrial production.

Tasks:

1. to analyze current designs and technologies of automated glue dispensing systems;
2. to identify the requirements, materials, and components for 3D printer platform modification;
3. to implement mechanical, electrical, and control system modifications on 3D printer platform for precise adhesive dispensing;
4. to conduct experimental testing of the improved system;
5. to evaluate the performance, accuracy, and reliability of the developed dispenser;

3. Main Requirements and Conditions

The system must automatically dispense adhesive along predefined paths
The system must be capable of processing typical industrial adhesive materials
The dispenser must allow adjustment of dispensing parameters (flow rate, speed, start/stop control).
Positioning accuracy ±0.1–0.5 mm.

4. Additional Requirements for the Project, Report and its Annexes

Not applicable

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Supervisor	Sigita Urbaitė		26/02/2026
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Mačerinskas Mantas. Development of Automated Adhesive Dispensing System Based on 3D Printer Platform. Master's Final Degree Project, supervisor Assoc. Prof. Dr. Sigita Urbaitė; Faculty of Mechanical Engineering and Design, Kaunas University of Technology.

Study field and area (study field group): Production and Manufacturing Engineering (E10), Engineering Sciences (E).

Keywords: dispensing; 3D printer; system; geometrical code; viscosity; precision.

Kaunas, 2026. 67 p.

Summary

To create an automated adhesive dispensing system using a 3D printer, a detailed study of dispensing methods was performed. Most common methods, such as syringe-type, contact transfer, and non-contact dispensing methods, were analyzed to understand which of these solutions would be the perfect fit. Through methods such as the design selection matrix and defining the necessary system requirements, goals were set that the system should achieve. The volumetric dispensing method was selected because this system matched the needed viscosity ranges and precision on the bead width that was necessary to achieve. A deep dive into the components was also performed to understand the factors of the geometrical code and the importance of configuring the system correctly. The existing 3D printer platform components were defined to understand what modifications need to be made. Then the pneumatic system was determined what devices should be added to sustain the supplied pressured air. The old tool of the 3D printer was removed, and the design of the parts that will be included in the system was made. The components that were printed included the mounting, push, and holding parts. Finally, the overall system was assembled and calibrated to ensure that the system worked and the movement was accurate. With the use of geometrical code, the movement of the dispenser was defined and tested. Programs were created to follow the desired path of the part that was provided and to perform the automated dispensing process.

Mačerinskas Mantas. Automatinės klijų dozavimo sistemos, pagrįstos 3D spausdintuvo platforma, kūrimas. Magistro baigiamasis projektas, vadovė doc. dr. Sigita Urbaitė; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.

Studijų kryptis ir sritis (studijų krypčių grupė): Gamybos inžinerija (E10), Inžinerijos mokslai (E).

Reikšminiai žodžiai: 3D spausdintuvas; sistema; geometrinis kodas; klampumas; tikslumas.

Kaunas, 2026. 67 p.

Santrauka

Siekiant sukurti automatizuotą klijų dozavimo sistemą, naudojant 3D spausdintuvą, buvo atliktas išsamus dozavimo metodų tyrimas. Siekiant suprasti, kuris metodas tinkamiausias, išanalizuoti dažniausiai pasitaikantys metodai – švirkštinis, kontaktinis pernešimas ir bekontaktis dozavimas. Pagal projektavimo parinkimo matricą ir apibrėžtus būtinus sistemos reikalavimus, nustatyti tikslai, kuriuos dozavimo sistema turi pasiekti. Pasirinktas metodas – tūrinis dozavimo metodas, nes ši sistema atitiko reikiamus klampumo diapazonus ir tikslumą, kurį reikia pasiekti dozavimo linijos plote. Atliktas išsamus komponentų tyrimas, siekiant suprasti geometrinio kodo įtaką ir teisingo sistemos konfigūravimo svarbą. Apibrėžti esami 3D spausdintuvo komponentai, siekiant nuspręsti, kokius pakeitimus reikia atlikti. Nustatyta pneumatinė sistema ir įtaisai, kurie turėtų būti pridėti, siekiant palaikyti suspausto oro tiekimą. Pašalintas senas 3D spausdintuvo įrankis ir suprojektuota nauja dalis sukurti dozavimo sistemai. Atspausdinti įvairūs komponentai - tvirtinimo, stūmimo ir laikymo dalys. Galiausiai surinkta bendra sistema ir atliktas kalibravimas, siekiant įsitikinti, kad sistema veikia ir judėjimas yra tikslus. Naudojant geometrinį kodą, buvo apibrėžtas ir išbandytas dozatoriaus judėjimas. Parašytos programos, kurių pagalba dozatorius veikė tinkamai.

Table of Contents

List of Figures

List of Tables

Introduction

The fourth industrial revolution has become a large part of today's manufacturing; many companies are looking for ways to convert standard processes into automated ones, which provide advantages such as reliability, efficiency, and low price [1]. Adhesive dispensing is one of them; these systems are used in fields where bonding properties are necessary, such as electronics, packaging, aerospace, and automotive manufacturing [2]. In these fields, quality and cycle time are dependent on the materials' extrusion [2]. Although this process is usually performed through manual application, they provide disadvantages such as inaccuracy, high assembly time, and a lack of knowledge, which leads to the final product error and waste material production [3] Because of these reasons, new automated methods are receiving more interest, which would "upgrade" this manufacturing process in various companies [2]. Existing 3D printers provide a great framework for creating new automated solutions, with their movement control, geometrical code understanding, precision, and low modification cost, which are suitable for integrating dispensing systems [4, 5]. Creating an automated dispensing system on this platform creates an advantage compared to the already manufactured systems, which are low-cost [6]. To create a roadmap, which would provide key points on how to modify an existing system, an analysis of the existing dispensing methods must be conducted [7]. Each solution provides different viscosity and precision ranges, which are important aspects in choosing the right process [7]. The dispensing process relies on the adhesive materials' properties; identifying these requirements provides the necessary settings for the modified system [8]. Other factors should also be considered, such as the method's complexity, adaptability to other frameworks, and cost. Through useful tools like the design selection matrix, this decision can be made.

This project aims to develop a reliable, automated glue-dispensing system based on a 3D printer platform. The already existing system must be analysed and researched to understand what needs to be changed and what should be left [2]. The working principles of controllers, motors, actuators, and sensors must be studied to provide an insight into the connections made between them [2]. Additionally, understanding how movement can be provided to the system is important; how you can determine where the dispenser will travel should be defined [2]. Also, new components must be proposed for the system, which would help perform the dispensing actions and determine through what methods they will come to life [2]. In the end, this final project should provide a roadmap for what decisions should be made and what adjustments should be performed to create a dispensing system suitable for use in industrial production. To create a low-cost system that would rival the existing solutions, which have a high cost, and would provide benefits such as accuracy, low maintenance, customization, and reliability.

Aim: to develop a reliable automated glue dispensing system based on a 3D printer platform suitable for use in industrial production.
Tasks:

1. to analyze current designs and technologies of automated glue dispensing systems;
2. to identify the requirements, materials, and components for 3D printer platform modification;
3. to implement mechanical, electrical, and control system modifications on 3D printer platform for precise adhesive dispensing;
4. to conduct experimental testing of the improved system;
5. to evaluate the performance, accuracy, and reliability of the developed dispenser;

Hypothesis: The system dispenses the glue correctly according to the requirements.

1. Automated Glue Dispensing Systems

The manufacturing industry is being changed, with new, more flexible, modern, and intelligent methods that provide various advantages over the existing ones [1]. This increase in research and development of new ways to manufacture different objects can be attributed to the fourth industrial revolution [1]. Where tasks commonly performed by human labour are replaced with innovative methods that provide various advantages [1]. According to the research performed by Gábor Mélypataki on Industry 4.0, by the year 2030, about 40% of work positions in Eastern Europe could be replaced by automated solutions [1]. So, adapting new and innovative solutions into the work environment could provide an edge in staying ahead of the competition [1].

One of the processes of manufacturing is glue dispensing, in which multiple components are glued together to produce a result [2]. This area requires precision, stability, and perfect layering; these parts can be achieved by implementing new and innovative methods into the manufacturing process [1, 2]. Also, by „upgrading“ these methods, other benefits such as an increase in accuracy and a decrease in performance time, cost, defects, and other similar attributes [1, 9]. Various methods are adapted to today‘s manufacturing process to dispense glue on the necessary parts [2]. Depending on the size of the company, the products, and the budget, different devices or human resources can be used to perform these actions [2, 9]. For small companies that use glue for their products, manual labour is one of the go-to solutions, because the cost of automated systems is high [10]. Size is also another important part in adapting new methods, for example, companies that produce furniture must use glue for bigger parts, and a certain size of device should be designed or used, which could also increase the cost exponentially [10]. An example of this manufactured solution is demonstrated in Fig. 1. [11].

Fig. 1. Adhesive Dispensing Machine 3-Axis E Series Automated Fluid Dispensing Robot [11]

The dispensing machine shown in the figure above is produced by Nordson and is usually used in the assembly of electronics [11]. It is one of the more popular solutions in this industry; depending on the product, various advantages can be achieved [10]. Although most of these manufacturers provide automated systems to certain fields, the price and lack of versatility could be one of the factors that would affect the company's decision to choose them [10]. A few of the more popular solutions are presented in Table 1.

Table 1. Automated Adhesive Dispensing Machines

Automated adhesive dispensing machine	**Price**	**Parameters**
Nordson 3-Axis E Series Automated Fluid Dispensing robot [11]	9000 - 16 000 Euros [11]	The system is used in the assembly of electronic chips [11]. Depending on the model, the ranges differ: – The area of operation from 200mm x 200mm x 50mm to 510mm x 510mm x 150 mm [11]. – Maximum speed from 500 mm/s to 800 mm/s [11]. – Precision ±0.008 mm[11]. – Maximum weight of processed material from 5 kg to 10 kg [11].
Musashi Engineering Shotmaster SX series [12]	9000 – 12 000 Euros [12]	The system is used for the assembly of electronic, automotive, and medical devices [12] Depending on the model, the ranges differ: – The area of operation from 100mm x 200mm x 50mm to 500mm x 500mm x 80mm [12] – Maximum speed 800 mm/s [12] – Precision ±0.01 mm [12] – Maximum weight of processed material from 8kg to 15kg [12]
Fisnar F4000 ADVANCE Series 4-Axis Benchtop Robot [13].	9500 – 17 000 Euros [13]	The system is used for bonding processes of various materials, coatings, and sealing [13]. Depending on the model, the ranges differ: – The area of operation from 300mm x 300mm x 150mm to 600mm x 500mm x 150mm [13]. – Maximum speed 800 mm/s [13]. – Precision ±0.008 mm [13]. – Maximum weight of processed material 10 kg [13].
SECOND 3 Axis Floor Standing Platform CCD Visual EMS SMT PCB Automatic Glue Dispenser Dispensing Machine SEC-551B Adhesive dispenser [14]	22 000 – 26 000 Euros [14]	The system is used for bonding processes of electronic components and two-component adhesive dispensing [14]. The system has an integrated visual inspection system [14]. Parameters of the system: – The area of operation from 500mm x 500mm x 100 mm [14]. – Maximum speed 800 mm/s [14]. – Precision ±0.015 mm [14]. – Maximum weight of processed material 5 kg [14].

The differences among certain “flagship” machines are shown in the table above. Systems that use adhesive dispensing methods do not have a big difference between the costs, but when additional tools are added, such as visual inspection, the price increases [14]. Depending on the size of the company, these solutions can be unattainable and lack the necessary flexibility, which could be expected [10]. Another approach for how companies can implement dispensing systems in their manufacturing is demonstrated in Fig. 2. [2].

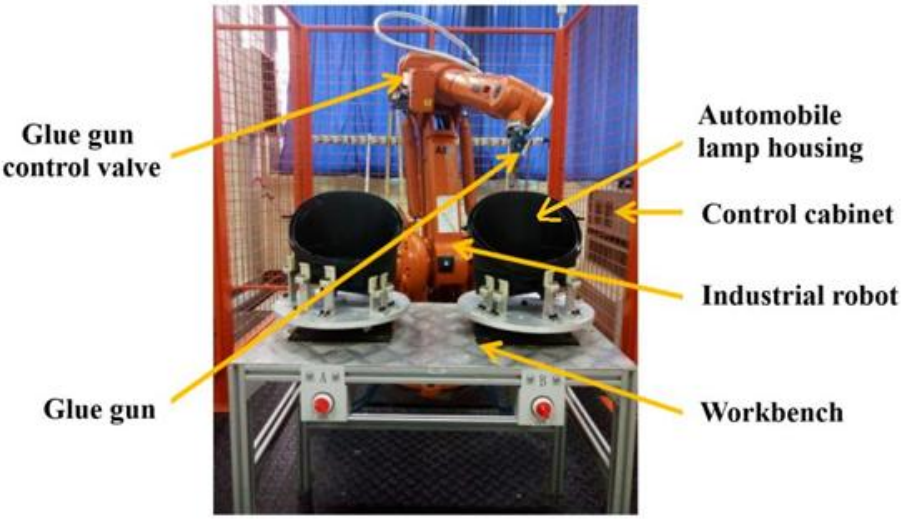


Fig. 2. Composition of the Automotive Lamp Housing Gluing System [2]

In the figure above, an automated robotic system researched by Xuelei Wang, which is designed for dispensing glue on lamp housing, can be seen [2]. These types of solutions provide a lot of benefits, such as scalability, speed increase, and flexibility, but they also have a few drawbacks for companies with a limited budget [2]. Developing, designing, and adapting robotic systems requires a lot of money and testing, and the payback on these systems may not be enough for companies looking for solutions [2]. For these reasons, new, quite cheap, and innovative methods should be developed and researched to provide an accessible solution [10].

Although a lot of companies use human resources for these types of actions and see this solution as the most optimal, there are still disadvantages that may not be considered [3]. Human error could damage various aspects of the process, from the setup to the finished product [3]. In the long run, these causes could increase the process time and reduce the quality of the products that reach the client, damaging the company's reputation [15]. In the glue dispensing process, errors such as nozzle offset could be attributed to human error, because visually, an offset of 0.1 mm could be hard to see with the eyes [3]. If the process is performed manually, there could be even more space for error, and the glue would be dispensed incorrectly, resulting in incorrect bond line thickness, path deviation, or gaps, which would reduce the quality of the final product [3]. This defective product could then reach the client and, in the long run, cause problems not only for the client but also for the company that produced it [3]. As mentioned, human error could also occur in the setup phase, where the mixture used for dispensing could be prepared incorrectly, resulting in an incorrect bonding process [15]. Lack of knowledge is another factor that leads to the overlook of environmental or time-related impacts [16, 17]. People performing this process could take too long to place the component on the dispensed glue, which in turn dries over time and could lose its bonding properties [16]. Taking note of the environment and adjusting the process is also important because if the temperature rises in the area where the process is performed, the glue flow changes, creating irregularities during dispensing [17]. All these mistakes can be attributed to human error, which could be solved by optimizing and „upgrading“ the process.

1.1. Dispensing Method

Glue material is an adhesive material that has the properties of bonding two objects together. Various dispensing methods are used to extrude the bonding material on one object, so the other can be placed and connected [7]. These solutions have various strengths and limitations, so choosing the right method is important to achieve the necessary result [7]. For glue, one of the most common dispensing methods is manual extrusion [7]. Where a person squeezes the tube of glue or uses a caulking gun to expel the material through the nozzle manually [7]. But for automated systems, other dispensing methods are used, where a system dispenses the adhesive material using different technical solutions [7, 16].

Dispensing methods can be grouped into certain categories, although according to the research paper „Silicon photon co-packaging: Adhesive dispense challenge and control“ written by Paul Gond-Charton [7]. There are three primary methods: time-pressure, pin-transfer, and non-contact jet dispensing [7]. They fall into a larger group: syringe, contact transfer, and non-contact [7, 16, 18]. Different methods provide varying advantages and disadvantages to the process, so choosing the right one is important to achieve the necessary result [19].

In some cases, these methods are combined to achieve successful bonding. An example of this can be seen in the research performed by Lui Huifang in „A new method for ultra-micro adhesive dispensing using a helical pipette needle“, where the adhesive material needs to be dispensed on a small microelectronics product [19]. Because of the size, a combination of time-pressure and pin-transfer dispense method was used by the researcher to achieve the necessary dispensed adhesive properties [19]. To get the necessary result in this process, a few things should be considered: the adhesive material, product, limitations, and strengths [7, 16, 18, 19].

1.1.1. Syringe Dispense Methods

Syringe dispense methods are a broad term used for solutions that involve a holding barrel for adhesive material, which is then pushed through the nozzle using different forces [16]. One of these systems is the time-pressure dispense system; an example is demonstrated in Fig. 3. [7, 20]. This type of dispenser uses air pressure to push the adhesive material through the needle to extrude a line of adhesive material on the surface of the product that needs to be bonded [7, 16]. Also, the time-pressure dispensing system has an additional function; the extrusion process can be performed using determined time intervals [7, 16]. Where the valve can close and open according to the setting that is input into the system [7, 16]. This option creates a possibility to create discontinuous patterns, unlike in the pneumatic dispensing system, which is also a part of the syringe dispense methods, but in this type of solution, the extrusion process starts and stops with the movement of the automated system [3, 16].

Both methods have their advantages and disadvantages when compared [3, 7, 16]. Time-pressure dispense systems have advantages such as precise volumetric control, which allows the adhesive material to be extruded on difficult surfaces, where there are areas that do not need to be covered [16]. This also reduces the amount of waste material, because only the essential areas can be bonded [16]. Pneumatic dispense systems have other advantages compared to the above-mentioned process [7, 16, 21]. One of them is the speed at which the extrusion is complete [7, 16, 21]. If the path is long, continuous working is faster, because in the time-pressure dispensing system, the pressure must increase and decrease during the dispensing [7, 16]. Another benefit is the structure and uniformity, because the adhesive material is placed in a constant line, there is a smaller chance for leaks and failures of bonding [7, 16].

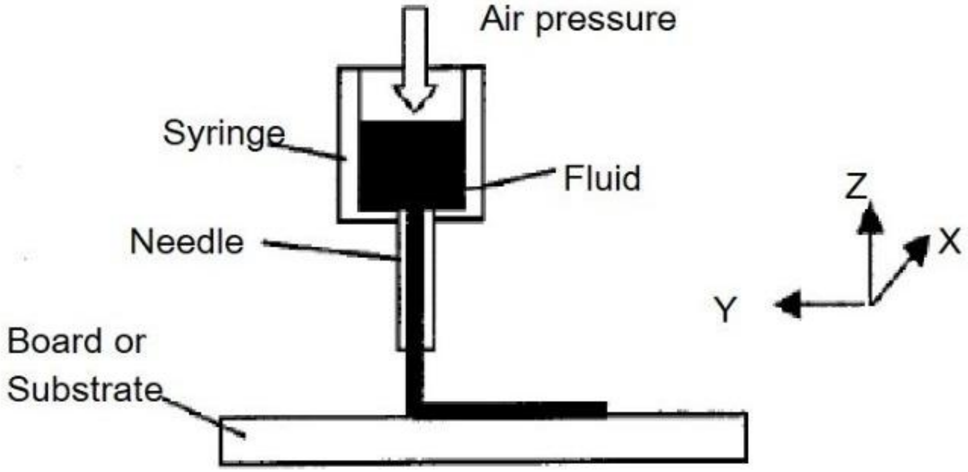


Fig. 3. Example of a Time-Pressure Dispense System [20]

Another method, which is part of syringe methods, is the volumetric dispensing, where, instead of air-pressure, a pneumatic or mechanical actuator is used to extrude the adhesive material [21]. In these cases, the material is pushed through the nozzle using the forces applied by the mechanism, which could vary depending on the solution [21]. These systems are designed to push the piston a certain distance, depending on the actuator type, either pneumatic or mechanical; a different result is achieved [21]. The use of mechanical actuators provides benefits such as an increase in precision and viscosity independence, which means that if the adhesive material changes due to a temperature change, the process of dispensing does not change [7, 21]. But there are also some disadvantages to adopting this type of process, such as the complexity of the mechanism, maintenance required, and weight, which could impact the process by creating vibration if installed incorrectly [7, 21]. The pneumatic actuator has a simpler design, and does not require as much maintenance, and it provides advantages such as lighter weight, lower cost, higher process speed, and higher durability over the mechanical actuator [7, 21]. But it also has some disadvantages, such as a lack of control over the piston, which is either pushing out or in, and it requires a source of compressed air for the process to occur [7, 21]. Movement can also cause more noise compared to the mechanical solution [7, 21]. All syringe-type methods dispense the material in lines [7, 16]. This is one of the factors that identify these types of systems [7, 16]. These types of solutions are one of the most common in the manufacturing industry [2].

Two other criteria determine if the dispensing method is suitable for the adhesive material selected [7, 16, 22]. One of them is the viscosity range, which helps determine whether the adhesive material parameter is suitable for the selected method [7, 16]. The other is precision, which determines how consistently the system dispenses material on the surface [22]. Each method has different values for both parameters, as shown in Table 2.

Table 2. Viscosity Ranges and Precision for Syringe Dispense Methods

Dispensing method	Viscosity ranges	Precision
Time-pressure dispensing	Low – Medium (1 – 50 000 cps) [7, 23]	±5% - ±10% [16, 23]
Pneumatic dispensing	Medium – Ultra-High (10 000 – 1 000 000 cps) [24]	±3% - ±5% [16, 24]
Volumetric dispensing (pneumatic actuator)	Low – High (1 – 500 000 cps) [25-27]	±1% - ±3% [25]
Volumetric dispensing (mechanical actuator)	Low – Ultra-High (1 – 1 000 000 cps) [28]	±1% [28]

This information provides insight into how these processes perform. Viscosity ranges are important because they determine if the material can be dispensed onto the surface of the product [16]. Depending on the adhesive, the viscosity changes; for example, water has 1 cps, and honey has 14095 cps [29, 30]. So, ranges determine if the material can be processed, while precision shows how accurate the deposition is and how consistent it is every cycle [22].

1.1.2. Contact Transfer Dispensing

Contact transfer dispensing is another method that could be used to place adhesive materials on the surface of an object that needs to be bonded [7]. This process is different compared to syringe extrusion solution; in these types of systems, the adhesive is placed in drops and not in lines [7, 16]. An example of one of these solutions, a pin-transfer dispense system, is demonstrated in Fig. 4. [7, 31]. In the image, the process can be seen where the adhesive is placed in the area that is called the flux dip, from which the system collects and transfers the bonding material on the surface [7]. The system is equipped with pins that dip into the container and move the adhesive onto the area of the object that is being processed [7].

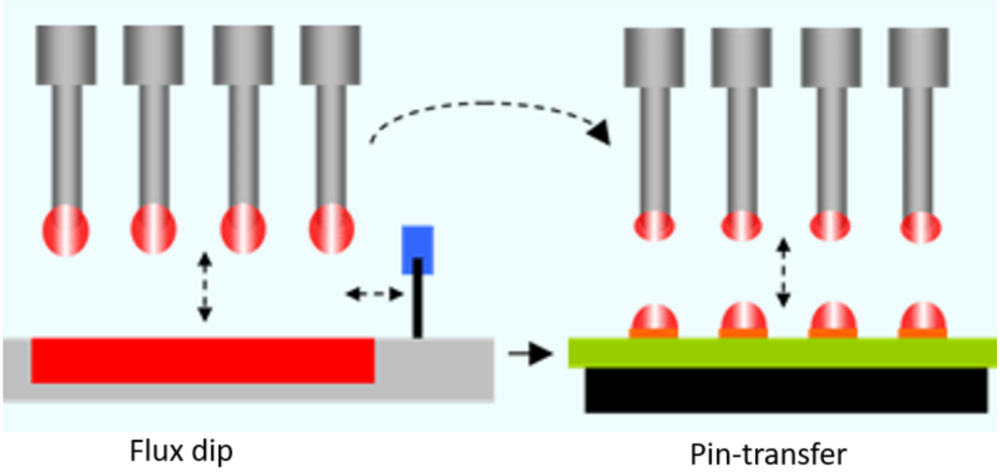


Fig. 4. Example of a Pin-Transfer Dispense System [31]

This type of adaptation provides various advantages, such as high process speed [7]. There could be hundreds of pins attached to the system, which provide a higher covering range, and the adhesive could be dispensed faster [7]. Another benefit comes in high precision, because the system is designed to place the material identically, the dots do not vary a lot, and a similar amount is deposited at each spot [7, 32]. Compared to syringe-type methods, things like clogging and the need for extra pressure change to clean the area where the adhesive material is stored are not necessary and are not present in the pin-transfer solution [7, 32]. Low maintenance and handling of materials with high viscosity are other benefits of this system, but it also has some disadvantages [7, 32]. The lack of flexibility is one of them, because the system is designed to dispense the adhesive in a certain pattern [7, 32]. If the product changes properties, the solution must be remanufactured, which comes with a high cost and becomes a bad choice for prototyping [7, 32]. Another issue is the open area where the adhesive is stored, which could get contaminated, and the cleaning complexity [7, 32]. If there are a couple of hundred pins, preparing them will take some time [7, 32]. Lastly, the volume of the adhesive that is dispensed cannot be controlled; the system can be set for one pin to transfer 3nL and another 6nL, but if the volume should be changed, the switch of pins should be performed manually [7, 32].

Stamping is another method of contact transfer dispensing, where, instead of pins transferring the adhesive materials, pads are used [16, 33]. The working principle is quite similar to the one mentioned above; the only difference is that instead of pins, pads are used to dispense the material on the surface of the product [16, 33]. This type of system has the same disadvantages related to the area where the material is stored [16, 33]. There are quite a few advantages also, one is that compared to the pin-transfer, more dispensing on more irregular surfaces is possible using pads [16, 33]. Covering area is another benefit of this solution; the design of the transfer mechanism is made to lay out the material onto a certain surface [16, 33]. But this could also be a disadvantage, because they are made in certain sizes, so if the product changes, a new pad should also be manufactured [16, 33, 34]. This also comes with a high cost and maintenance, because there should be multiple pads manufactured to fit products of different structures and sizes, and the change is performed manually [16, 33, 34]. Viscosity ranges and precision should also be considered, as with syringe-type dispensing methods. Parameters of pin-transfer dispensing and pad stamping can be seen in Table 3.

Table 3. Viscosity Ranges and Precision for Contact Transfer Dispense Methods

Dispensing method	**Viscosity ranges**	**Precision**
Pin-transfer dispensing	Medium – High (50 000 – 500 000 cps) [7, 32]	±2% - ±5% [7, 32]
Pad stamping	Low – High (1 000 – 100 000 cps) [16, 33, 34]	±5% - ±10% [16, 33, 34]

Viscosity ranges for pin-transfer dispensing indicate that not all adhesive materials can be used with this system, this is because of the design of the pins [7, 32]. Where certain materials can only stick to them, unlike in pad stamping, which could be used for materials of lower viscosity [7, 16, 32-34].

1.1.3. Non-Contact Dispensing

The non-contact dispensing method is the last process that can be used for adhesive material extrusion. One of the main categories of this solution is non-contact jetting, which has a few different variations in how the system works [7]. An example is demonstrated in Fig. 5., unlike in the syringe or contact transfer dispensing solutions, here the material is „shot“ or sprayed onto the surface of the product [7]. There are three types of solutions for this type of system: piezoelectric, pneumatic, and solenoid valve jetting [35-37]. Choosing the correct one is important because every single one of them provides different advantages and disadvantages [35-37]. These types of systems also resemble contact transfer dispensing, in which the adhesive material is taken from the storage area [35-37].

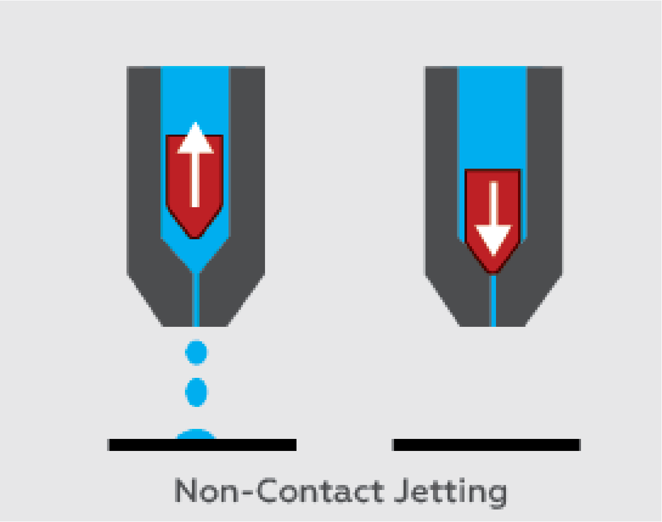


Fig. 5. Example of a Non-Contact Jetting System [38]

Piezoelectric jetting stores the material inside an area near the nozzle, which is kept under a certain pressure [35]. This property is usually kept low to prevent dripping and contain the adhesive [35]. After the system is filled, energy is applied so that the piezoelectric material can expand, and the dispensing process begins [35]. Then the adhesive is ejected through the nozzle using a piston, which moves inside the mechanism to perform the dispensing [35]. After the material in the storage area is depleted, the piezoelectric mechanism closes until it is filled again [35]. This type of solution provides various advantages, one of which is speed, which is higher compared to the contact-transfer method, because the nozzle is not required to move down [35]. Also, the piezoelectric mechanism works fast, making the dispensing process quick [35]. Another benefit is product protection, because this system is non-contact; the nozzle never reaches it [35]. The implemented control software also allows more flexibility over the process movement of the piezoelectric mechanism, which can be set to various parameters to achieve the necessary result [35]. But some drawbacks come with this method, of which complexity, maintenance, and cost are three of the more important ones when considering piezoelectric jetting [35]. When introducing a new adhesive material, more adjustments, calculations, and expertise are required to make the dispensing process successful [35]. Compared to the syringe-type methods, where various materials can be used without the necessity of adjusting [7]. Because piezoelectric components are used, the initial cost of the system is high compared to pneumatic solutions [7, 35]. Also, the piston inside the device needs to be maintained frequently, because of the constant movement, it could be damaged by stress [7, 35].

Another non-contact dispensing method is pneumatic jetting, which is similar to the previously mentioned piezoelectric solution, but has a few key differences [35, 36]. The loading of adhesive material and the maintenance under certain conditions are the same in both systems [35, 36]. But pneumatic forces are used to dispense, not piezoelectric [35, 36]. Compressed air moves the mechanism inside, which then pushes the material through the nozzle, creating droplets [36]. After the adhesive storage is empty, the system resets and begins the process again [36]. Because no piezoelectric components are used, the cost of this type of solution is lower, and the components themselves are cheaper when a fix is needed [36, 39]. Because the pneumatic jetting system is not so complex, there are lower requirements for maintenance [36, 39]. Also, higher viscosity ranges can be achieved with compressed air, which can be increased if the material requires it [36, 39]. But some drawbacks come with this type of jetting; one of them is the lower speed compared to the piezoelectric solution [36, 39]. Because the compressed air limits the system, the process is dependent on it, and such high dispensing speeds cannot be achieved [36, 39]. Also, with heavy use, vibrations and precision irregularities can appear, caused by the movement of the internal mechanism [36, 39].

The last type of non-contact dispensing method is solenoid valve jetting, which, compared to pneumatic and piezoelectric solutions, is the simplest [37]. This type of system uses electromagnetic forces to create jetting, where a current is used to create a magnetic field [37]. One of the differences compared to the previously mentioned solutions is that the adhesive storage does not require low pressure; instead, the area is designed so that the needle inside the device holds it [35-37]. When the magnetic field is applied, the needle rises, which opens the nozzle for the material to drop, and when the current is not present, it lands and closes it [37]. This process is repeated to perform the dispensing action [37]. Simplicity makes this system the cheapest, requires the lowest maintenance, and is easy to integrate compared to the piezoelectric and pneumatic jetting [37, 40]. But this comes with some drawbacks; it is the slowest solution of non-contact methods, and the heat generated by the needle can change the properties of the adhesive material inside the storage area [37, 40].

Like in previous syringe-type and contact-transfer methods, the viscosity ranges and precisions were shown. For non-contact jetting dispensing, these parameters are also important because they show what materials can be used and how precisely the process will occur [7]. This data can be seen in Table 4.

Table 4. Viscosity Ranges and Precision for Non-Contact Dispense Methods

Dispensing method	**Viscosity ranges**	**Precision**
Piezoelectric jetting	Medium – High (50 000 – 100 000 cps) [35, 41]	±1% - ±2% [26, 32]
Pneumatic jetting	Low – Ultra High (1 – 1 000 000 cps) [36, 39]	±2% [36, 39]
Solenoid valve jetting	Low – Medium (1 – 50 000 cps) [37, 40]	±5% - ±10% [37, 40]

These viscosity ranges show that pneumatic jetting can be used with almost any adhesive material and has good precision [36, 39]. Other methods lack the range of materials that could be used in the process, but piezoelectric jetting has good precision results, and in certain cases, this would be a good solution [35, 41]. Solenoid valve, although the cheapest and least complex, is the weakest compared to other non-contact dispensing methods [37, 40].

1.2. Control Approaches

Choosing the correct dispensing method is not enough for the system to function correctly; therefore, various control approaches are implemented to ensure proper operation. For this type of solution, different steps must be set to „tell“ the machines how the adhesive material should be extruded onto the object [2]. Systems are usually put into two groups: open-loop and closed-loop approaches [42]. They determine the complexity of the system and are demonstrated in Fig. 6. [42, 43]. Open-loop has a simpler working principle: information is input through a controller, then this information travels to the mechanisms of the system, for the process to begin, and the result is achieved [42]. As demonstrated in the figure below, disturbances are not noticed by the solution [42]. While closed-loop has more sensors implemented into the system, to check various parameters during the process itself, and adjusts the controller settings or stops according to the received information [42]. These solutions are more complicated, and there is more room for errors that could occur; for this reason, the right configurations must be made, and the correct parts selected [42]. Otherwise, the system can be assembled, and the process will be performed incorrectly [42].

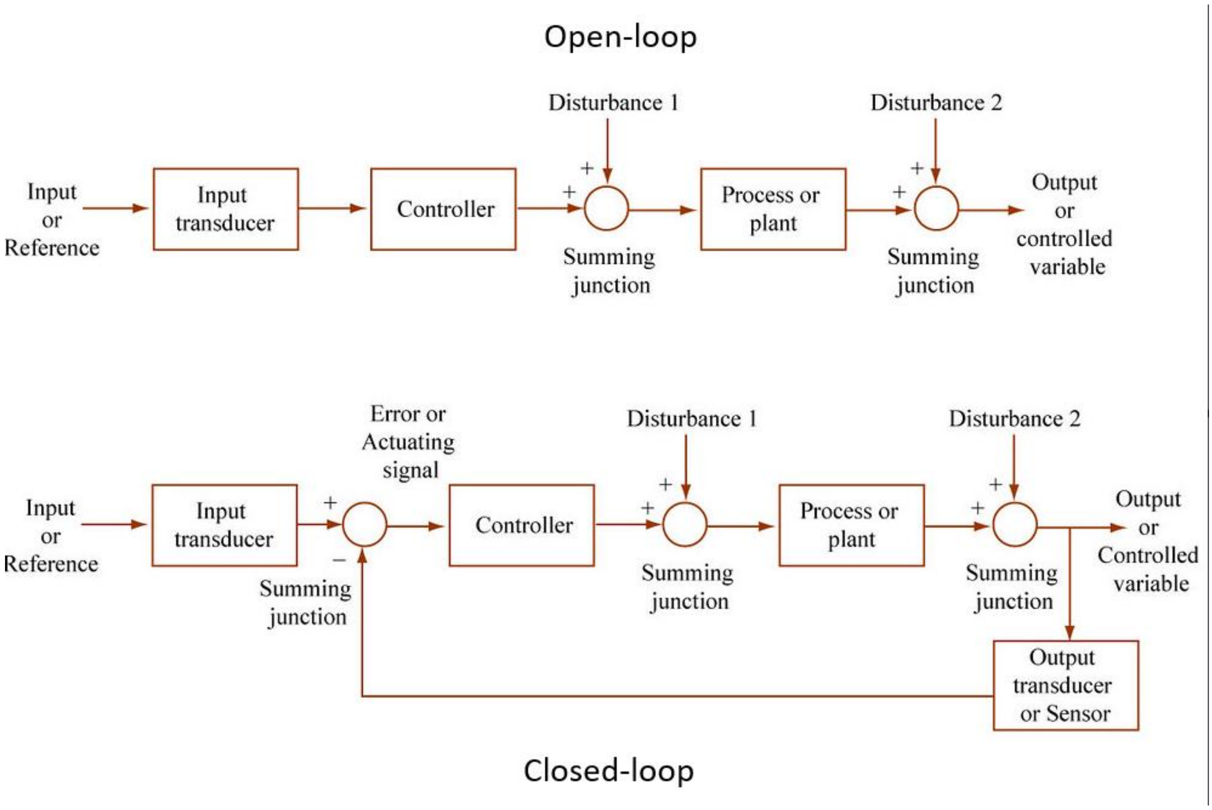


Fig. 6. Examples of Open-Loop and Closed-Loop systems [43]

Adhesive dispensing solutions use various control approaches that usually depend on the available capital of the company and the type of process required. An example of this could be the time-pressure dispensing method that can use an open-loop or a closed-loop approach [7, 42]. The more sensors and other devices are added to measure various parameters, the more complex the system becomes [42]. If the method mentioned above is open-loop, the process is simple by defining the path that needs to be extruded through the controller, the process will begin, and end after a set timer or completion setting [7, 42]. But if the system is required to measure parameters such as the amount of adhesive inside the storage area or temperature, additional sensors must be added, which turns it into a closed-loop solution [7, 42]. Then, during the dispensing, it would measure all factors altering the input and changing how the mechanism performs [7, 42]. Other modifications could also be made, such as adding a visual inspection system that evaluates the deposited material and changes the parameters according to it [3]. But some dispensing methods, such as piezoelectric and pneumatic jetting, are predominantly closed-loop, because these systems almost always come with sensors meant to measure the temperature or air pressure so that they won't be damaged [26, 32].

Controllers are the brain of the automated system, through which an operator usually interacts with the process [2, 44]. These devices usually have an integrated screen through which certain directions or actions can be input for the process, making it easy for the person to control the system [2, 44, 45]. Controllers for automated systems that use movement in their process and have implemented software, which is run and shown through the screen [2, 44]. These firmware's usually use „G-code“, which is a language that provides the system movement and speed regulations [2, 44]. Then it is run through mathematical models that send certain signals to the I/O components that provide information to the mechanical part of the system [2, 44]. Controllers also have processors that help perform the actions [2, 44, 45]. For dispensing systems, controllers are important because, through them, information such as the path, volume, and speed can be configured [3]. The quality of these devices is also important, depending on the dispensing method that needs to be achieved [2, 44]. Processing times can vary depending on the software that is being run and the internal components [2, 44]. If the system is closed-loop and there are various sensors, more data comes into the controller that needs to be calculated and processed, which means if the controller of a lower end is used, it will lag or will not produce an outcome at all [2, 44].

Another important component of the control approach is the I/O device, which works as a „translator“ from the controller to the machine [2]. These components receive commands from the controller in zeros and ones and turn them into electrical signals, which are then transmitted to the mechanism [2]. There are various types of I/O solutions available in the manufacturing industry, depending on the number of input and output ports [2]. They are demonstrated in Fig. 8 [46-49].

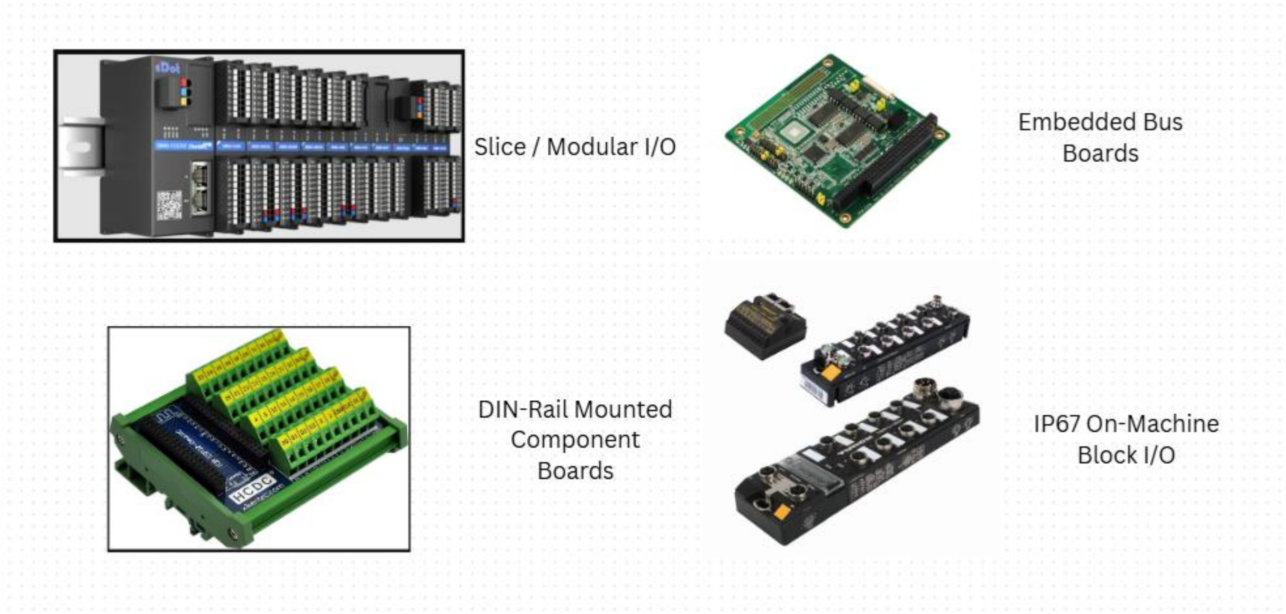


Fig. 7. Types of I/O Devices [46-49]

Different solutions of the I/O devices are presented in the figure above; they provide certain advantages and disadvantages for the system [46-49]. Depending on the scenario and the type of sensors that are implemented in the system, the device can differ [46-49]. For example, embedded bus boards are usually implemented in the controller's processor board, and if there are a few sensors, an additional device is not necessary [46-49]. Slice/Modular I/O provides connections for many inputs [46-49]. This provides a synchronization of various devices to be connected through one or two outputs [46-49]. The IP67 I/O device provides safety in areas where there is a lot of dust or where water resistance is required [46-49]. DIN-Rail provides mounting capabilities, which creates an organized solution [46-49]. Many of these I/O devices vary in size, providing more ports, if necessary, which means choosing the right solutions depends on the scale of the system [46-49]. Another factor that indicates what device should be used is quality[46-49]. Attributes like speed are important, especially in the non-contact dispensing solutions, where signals must be sent at a fast pace to open and close [35, 41]. For solenoid valve jetting, having a good I/O device is important because the needle inside needs to move at high frequencies to perform dispensing [37, 40]. For other methods, depending on whether the system is open-loop or closed-loop, the necessity of a good quality device could vary [2, 42]. Because for a system that only moves according to the path provided and the dispensing methods use only an actuator, a more basic and cheaper I/O device can be used [2].

Another component of the system is the mechanical part, which receives the "translated" information from the I/O device [2, 4, 5]. Depending on the dispensing method, various solutions can be used, but usually one thing is always present: the motors that create the movement in the x, y, and z axes [2, 4, 5]. Motor drivers are used to process this information into steps, which prevent the mechanism from moving at full force [2, 4, 5]. For the dispensing system, they always have an operating device, which begins the process simultaneously with the movement [2, 4, 5]. Solutions like the non-contact and contact-transfer dispensing use specially designed operating tools to perform the extrusion actions [7]. But volumetric solutions use linear actuators to perform the push action; they vary in operating power, between pneumatic and mechanical, also providing variations in their lengths to adapt to various systems [50]. These devices vary in quality; for example, non-contact jetting requires high frequencies to open and close at fast paces, so using a low-capability solution would provide errors in the process. For non-contact jetting, high frequencies are used, which provide the movements inside the dispensing heads [7].

1.2.1. Failure Models

There are various ways the system can fail to perform the provided actions. Depending on whether the system is open-loop or closed-loop, different errors can occur, which would impact the result [42]. Especially in adhesive dispensing systems, where a failed process could lead to increased waste material, reduced bonding time, and irregularly dispensed material [2, 44]. For open-loop dispensing systems, failure models:

- Viscosity change – because the system is open-loop, it does not have sensors, which provide information about how the adhesive changes [2, 44]. This means that attributes such as temperature changes and dust will not be noticed, and the dispensing process will continue [2, 44].
- Inaccurate bead width – this is caused by different factors, such as temperature change, path deviation, and contamination of the nozzle [51]. Because there are no extra sensors or visual devices to provide information on the result, this could occur in open-loop systems [2, 44].
- Operating at wrong inputs – this is also caused by the lack of sensors; the area where the adhesive material is stored could be empty, and the process would still be performed [2, 44].

Closed-loop systems have more devices, which are used to prevent the errors that are mentioned above, but they still can have some errors in their process [2, 44]. Closed-loop dispensing systems failure models:

- Inaccurate sensor information – because various sensors are used, they can produce inaccurate information for the system [2, 44]. This can cause various issues, such as showing the

temperature incorrectly or wrong measurements of the adhesive materials in the storage area [2, 44].
- Process issues – they can be caused by an incorrectly configured system, which would not work in unison, making the process inaccurate [2, 44]. It is an important step in creating these kinds of systems and requires knowledge and understanding of how everything should be connected to produce a successful result [2, 44].

Certain components of the system could also be responsible for failure in the process [2, 44]. Quality is usually a factor in these cases, where a lack of technology provides unavailability [2, 44]. Controller failure models:

- Processing error – caused by the low-quality processor, which cannot handle the information that is going into it [7, 42]. Depending on the size of the system and how many components there are, certain parts should be selected or upgraded [7, 42]. Otherwise, this would create lag and timing issues [7, 42].
- Software issues – controllers use certain operating systems to understand the input that it receives from the operator [2, 44]. This could cause issues if the programs or mathematical models are written incorrectly, making the controller produce an error message or not start the process [2, 44].
- Damaged interface – if the system is in the manufacturing area, the screen can be damaged by outside factors [2, 44]. This could make the infare detach or create damage, preventing the operator from using this system [2, 44]. Other issues, such as heat or electrical noise, can cause the controller to send incorrect signals to the I/O devices [2, 44].

I/O devices:

- Electrical issue – this is caused if the I/O device is not wired correctly [2]. Damages to the device itself can occur, or issues with the process can be more noticeable [2].
- Lag issue – this is caused if the I/O device is of lower quality, if this device receives many various signals from the controller, and it’s not suited to process this information [2]. Lag could occur, making the command travel to the mechanical components at the incorrect time, creating issues with the dispensing process [2].

Mechanical components:

- Wear issue – mechanical components such as belts, motors, and operating devices can have wear issues over time [2, 4, 5]. Creating errors in the movements of the axes and issues with the dispensing process [2, 4, 5].
- Heat accumulation issue – in the area where the system operates, heat can accumulate, leading to missed steps or irregular working of the system [2, 4, 5].
- Process lag – if the components are not of the right properties, the process can be performed incorrectly [25, 28]. For example, if the selected linear actuator does not have enough length or strength to extrude the material through the nozzle, the adhesive material would be dispensed in incorrect amounts [25, 28].

When designing and developing systems that involve these components, various precautions should be taken [2, 44]. To ensure that the errors in the results would not occur, because providing a defective part would damage the company's trust and credibility [2, 44].

1.3. Chapter Summary

The theoretical analysis provided a view of today’s automated solutions for the dispensing systems. What factors indicate the selection of these methods, and what criteria should be aimed at to achieve a system that provides a balance between quality and cost [10]. A few automated dispensing machines were analysed and compared, providing the key aspects that should be aimed at [10]. Also, an analysis of the three main dispensing systems was performed, and the working principles were explained [7]. The syringe-type, contact-transfer, and non-contact dispensing methods and their solutions were explored, and the advantages and disadvantages were determined [7]. For each solution, the viscosity ranges and precision were found through the analysis of scientific articles and datasheets of existing products, which allows for a comparison between them [7]. A review of common control approaches was performed to provide information needed to develop a system [42]. The differences between open-loop and closed-loop systems in dispensing were determined [42]. How different components, such as controllers, I/O devices, and mechanical parts, impact the process was also analysed [42]. Failure models for these parts were also determined and analysed, providing actions that should be avoided to develop a system that performs actions properly [42]. This information gives an insight that is needed in the second chapter to decide on choosing the correct dispensing method and what approaches to take to develop a system that would perform the necessary actions.

2. 3D Printer Platform Modifications

3D printers are widely used across various manufacturing fields and provide a good framework for modification that could turn these systems into dispensers for adhesive materials. One of the attributes that is present in this type of solution, which is also important for dispense systems, is the ability to move in the x, y, and z axes [4, 5]. This movement provides the ability to print various products of different shapes and sizes, and it is also beneficial for dispensers, which must also expel the adhesive material on various surfaces [4, 5]. For this project, a custom-made 3D printer was provided by Company X, which, after years of use, did not match the required accuracy. This printer had to be reconstructed to be suitable as a dispensing system for the manufacture of electronic panels. The project was specific, and the traditional dispensing systems were too expensive.

Multiple steps were determined to successfully perform the modifications on the system. Although the 3D printer already provided a good framework to turn into an adhesive dispensing system. The printer's head must be redesigned into a dispenser, which means a dispensing method must be chosen [4, 5]. System requirements were identified, including the adhesive material to be used, precision, allowed cycle time, and other parameters necessary to achieve the desired result. Then, a design selection matrix was made to evaluate which dispensing method was the best fit with the mentioned requirements [52, 53]. Choosing the dispensing method was not enough to perform modifications to a system; the head of the 3D printer had to be redesigned, which means parts and devices had to be selected to achieve this task [2].

2.1. System Requirements for the Dispensing System

Defining the system requirements was an important step, which provided information on what modifications should be made to the platform. Firstly, the adhesive material used in the dispensing system was determined [8]. PCB adhesives were requested by Company X because the system had to provide versatility in the process, and the components provided were used in electronic devices [54]. Viscosity was an important parameter, which determined what solutions could be used with this material [8]. PCB adhesives were determined as the most suitable bonding material, which had an electric-grade advantage [54]. This material had properties such as good structural integrity and protection, which were important to maintain the electrical charge, which should be maintained when components are bonded [54]. The usage of these adhesives was noticed mostly in circuit boards, but there were examples where it was used to bond plastics, glass, and wood [54]. Manufacturers that produced these materials were analysed, and viscosity ranges were determined based on their products [54]. This data was presented in Table 5.

Table 5. PCB Adhesives Viscosity

PCB adhesive type	Viscosity
Cyanoacralyte	5 - 2400 cps [55-60]
Silicone one-part	5000 - 425 000 cps [61, 62]
Silicone two-part	50 – 500 000 cps [63]
Epoxy one-part	150 – 1 000 000 cps [64-66]
Epoxy two-part	500 – 500 000 cps [67, 68]
UV cure	115 – 275 000 [69, 70]
Structural acrylics	1 000 – 250 000 [71-74]

The viscosities provided in Table 4 were obtained from various manufacturers of this material. Ranges were determined based on the information provided and achieved at different temperatures, which were then summarized [55-74]. The lowest cps was achieved by cyanoacrylate, which had another name, which was super glue [55-59]. It was noticed that this material was used for various product bonding, such as electronic components, plastics, and wood [55-59]. The viscosity showed that the adhesive is quite thin, more like a water-based material [55-59]. Silicon had two different types: one-part, which had one component and did not require mixing [61, 62]. It was noticed that these adhesives provided various advantages, such as heat resistance and good absorption, which were used on products that require less vibration [61, 62]. Two-part silicone, according to the analysed information, had two different materials, which interacted with one another [63]. Resin was used for its sticking properties, and the other material was used for hardening, which was mixed [63]. Another adhesive that had similar one-part and two-part variations was epoxy; another difference was noticed compared to the listed PCB adhesives, this material was made from various products, which made certain solutions reach viscosities of 1 000 000 cps [64-68]. The advantages provided by the use of this material were heat resistance and good structure [64-68]. In the analysis of the UV-cure adhesives, a special property was noticed, that this material hardened under ultraviolet light [69, 70]. This meant that this material was used in areas where a high-speed process was required, because under these special conditions, the material cured at a fast pace [69, 70]. Lastly, structural acrylics were another type of PCB adhesive material [71-74]. The analysis provided that this material, in most cases, was made of two components and was used in areas where a fast cycle time was required, because of the properties, which identified that this material solidifies at a very fast pace [71-74].

Bead width is the second system requirement, which was determined. This indicated the dispensed adhesive materials' size, which had to match the components' bonding area [51]. Company X provided the component, which was demonstrated in Fig. 8., as the part on which the dispensing process had to occur. The red lines in the figure were used to mark the area of the path, which the automated dispensing system had to take.

Fig. 8. Part Provided by Company X, Red Lines Mark the Area Where the Adhesive Should Be Dispensed

Bead width was determined using measuring tools, which provided a 3mm size of the bonding area. Other measurements were also made, which provided information about the size of the components. The length of the part in the middle was 245 mm, and the width at the lowest part was 145mm, and at the top was 140mm. This information provided insight, which was used to determine the working area of the system. It also provided possibilities for multiple components to be processed. Through analysis, it was noticed that bead width was closely related to the nozzle of the dispensing system [51]. This information provided the requirements for choosing the right nozzle, which was of 3mm diameter [51]. Another analysed property that could affect the bead width was precision [7]. Precision was identified during the theoretical part for each method, which indicated how much volume was extruded each cycle [7]. It showed that each time the process was performed, the dispensed adhesives' properties were altered, related to the temperature change or unintentional hardening [8]. In cases where a certain evaluation system was implemented, the result was examined and fixed by changing the inputs of the process [7]. Some PCB adhesives also presented properties that affected the bead width size, such as thixotropy, which altered the material's properties under certain conditions [75]. This effect was described as the material consistency change; it was written that when the material was inside the storage area, it would be thick, and when force was applied, it would change structure to be extruded through the nozzle [75]. After the adhesive was dispensed, it restructured and regained its original phase [75]. For bead width, when extruded, it would look as if it does not match the requirements, but after a certain amount of time, it would come back to the needed width size [75]. When the adhesive material was chosen, it was ensured that the material had this effect or not [75]. The precision for this project needed to be as low as possible; the aforementioned factors were considered to lower it.

The accuracy required for the system was also determined; this factor was related to the mechanism itself. Analysis was performed on how this parameter affected the dispensed adhesive material, and if the system was inaccurate, the material would leak over the edges or impact the long-term structure of the product [76]. As mentioned, this is mostly achieved through calibration of the system so that it moved with the nozzle in sync, and that exact number of steps that were provided by the controller [76]. The system had to be set to follow the path of the component, which was shown in Fig. 8. [76]. Analysis performed provided another factor, which impacted the accuracy of the system, which was path selection [3]. This meant that if the system moved according to the push of a button accurately and during the dispensing process inaccurately, the adjustments had to be made to the written program [3].

The cycle time requirement was also determined; this factor was used to indicate the amount of time necessary for the system to complete the process. The performed analysis indicated that factors such as curing and path selection affected the time it took to complete a cycle [77]. If a fast cycle time had to be achieved, these properties had to be considered. Curing is an attribute which determined how fast the adhesive material will dry out and permanently bond the components [77]. For path selection, the most optimal solution had to be selected, which provided fast and accurate movement [3]. In the case of the component provided in Fig.8., the path was not difficult, but certain adjustments still needed to be made to achieve an optimal and accurate solution.

2.2. Design Selection Matrix

The design selection matrix was the tool used for determining the most suitable dispensing process for the 3D printer platform. During the analysis performed, this solution, also known as the Pugh matrix, was used in various fields, from engineering to product design [52, 53]. The factors by which the dispensing methods were evaluated were determined based on the theoretical research performed. This type of matrix was useful in weighing the options, categorizing them, and providing information for what solution was the most suitable option for this 3D printer platform [52, 53]. Based on theoretical research, a design selection matrix was made and depicted in Table 6. The points were assigned according to the created value system, where 1 was the worst score, and 5 was the best. As an example, solutions with the lowest viscosity ranges got 1, and with the highest, 5, they were assigned according to the performed theoretical research.

Table 6. Design Selection Matrix

Criteria	**Solution**								
	Time-pressure dispensing	Pneumatic dispensing	Volumetric dispensing (mechanical actuator)	Volumetric dispensing (pneumatic actuator)	Pin-transfer dispensing	Pad stamping	Piezoelectric jetting	Pneumatic jetting	Solenoid valve jetting
Viscosity range	1	4	5	4	3	2	2	5	1
Precision	1	2	5	3	2	1	4	3	1
Cost	5	5	1	4	3	3	1	2	2
Complexity	5	5	3	4	3	3	1	1	2
Adaptability	5	5	3	5	1	1	3	2	4
Total score	17	21	17	20	12	10	12	13	11

2.2.1. Viscosity Ranges

The first analysed criterion was the viscosity range; the results were given according to the analysed theoretical material, and the lowest results were given to time-pressure dispensing and solenoid valve jetting, which had low to medium viscosity ranges (1 – 50 000 cps) [7, 23, 37, 40]. Although they had the lowest limits, some adhesive materials can still be processed, especially the ones that are very thin [8]. Solenoid valve jetting had a low viscosity range, because of how the system was designed, the moving needle inside could get jammed if the adhesive materials were too thick [37, 40]. Time-pressure dispensing design was based on extruding the material in certain time intervals, which required big pressure changes [7, 23]. The process would then be performed incorrectly if a high viscosity material was used, because the pressure did not increase enough to push it out through the nozzle [7, 23]. Piezoelectric jetting was given the score 2, although it also had a limited viscosity range of medium to high (50 000 – 100 000 cps), it could handle higher thickness adhesive materials compared to the previous methods [35, 41]. The working principle of this system relied on the piezoelectric material that moved inside, and if the material was too thin, leaking would occur, and if it was too thick, it would not be jetted out [35, 41]. Pad stamping had a viscosity range of low to high (1 000 – 100 000 cps), which was better limits than the ones mentioned before, but had a quite low cap, because of this, it also received a score of 2 [16, 33, 34]. This solution was designed to collect the adhesive from the storage area and place it on the object, which used a mechanism to release it [16, 33, 34]. If the material was too thick, it would stick and cure on it, which required the need for replacement [16, 33, 34]. Pin-transfer dispensing also had viscosity ranges of medium to high (50 000 – 500 000 cps), but the value on the higher end was bigger; for this reason, it was given a score of 3 [7, 32]. In this solution, pins were used as the dispensing mechanism; lower viscosity adhesives would not stick to them, and when the material had a viscosity of ultra-high, the amount needed for accurate dispensing was inaccurate [7, 32]. Solutions that were given a score of 4 had viscosity ranges that allowed them to process almost every adhesive. In pneumatic dispensing, constant air pressure was used to push out the adhesive through the nozzle, which allowed various viscosity adhesives from medium to ultra-high (10 000 - 1 000 000 cps) to be used [16, 24]. Only thin materials were an exception, because the compressed air would not dispense at an accurate volume [16, 24]. Volumetric dispensing with a pneumatic actuator had a viscosity range from low to high (1 – 500 000 cps) [18]. This system worked by using a beam expelled by compressed air that pushed the adhesive material through the nozzle [18]. If the viscosity was too high, it would require more pressure, which would be dangerous and would cause damage [18]. The highest scores were given to volumetric dispensing (mechanical actuator) and pneumatic jetting. These methods provided the largest ranges from low to ultra-high (1 – 1 000 000 cps), which indicated that every adhesive material can be used [28, 36, 39]. Lastly, these limits can be summarized into a graph for better understanding, which can be seen in Fig. 9.

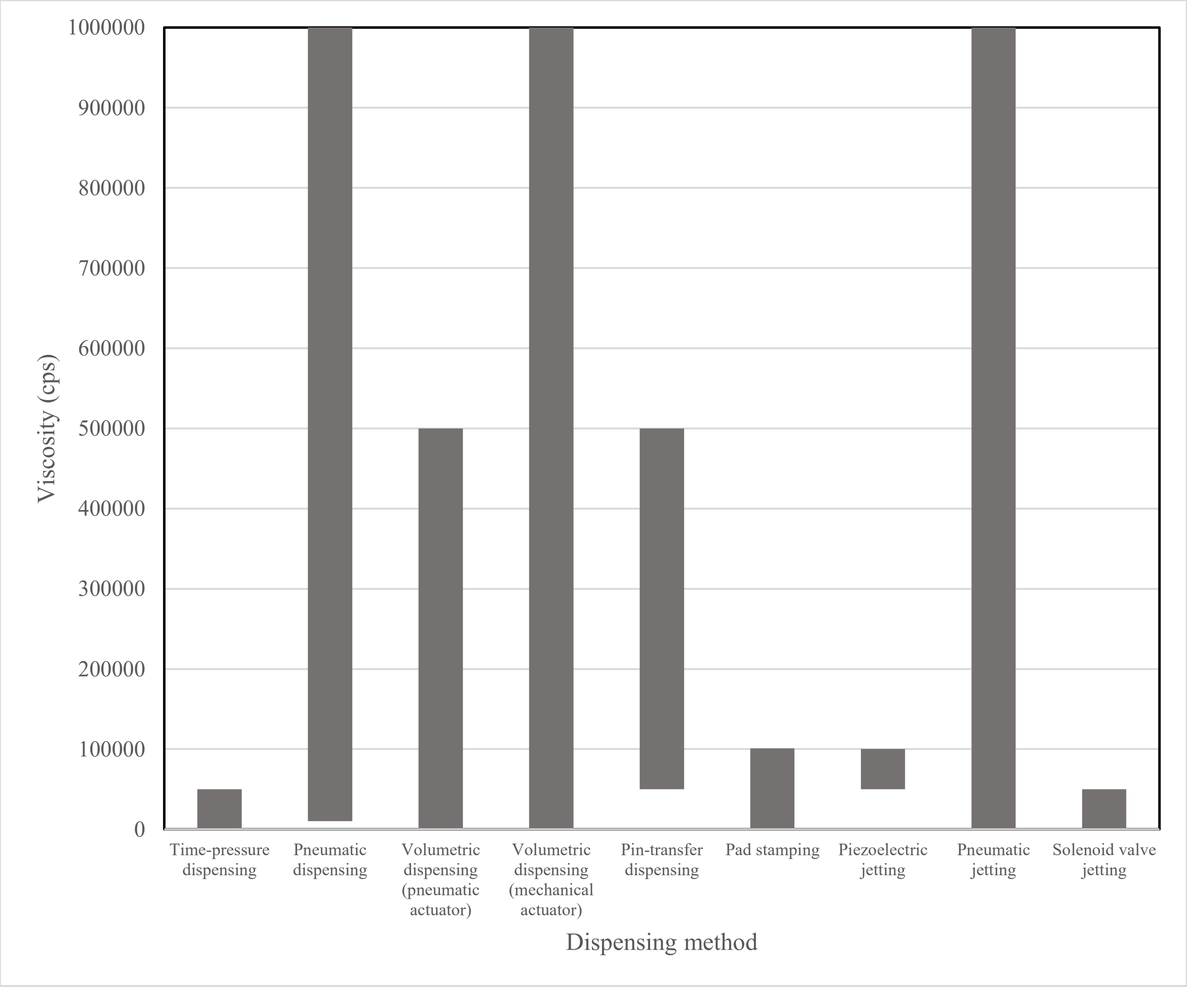


Fig. 9. Viscosity Ranges of the Mentioned Dispensing Methods

The ranges achieved from the figure were compared to the data provided in Table 5, which showed the ranges of the PCB adhesive that the system was required to process. Solutions that received the lowest score, which were time-pressure dispensing and solenoid valve jetting, will not be considered for a system that was required to be flexible with the material it processed [7, 23, 37, 40]. Only cyanoacrylate and a certain amount of low-viscosity PCB adhesives would be processed if these methods were used [55-60]. Piezoelectric jetting presented the issue, where its limit started at 50 000 cps, not even covering the previously mentioned cyanoacrylate adhesive [35, 41]. Pad stamping had a higher range than the previously mentioned methods, but still lacked the coverage of the thicker PCB adhesives [16, 33, 34]. To make the system more versatile, especially when talking about the PCB materials, the four solutions mentioned were not considered based on the result of the viscosity ranges. Pin-transfer dispensing provided quite a high ceiling, which almost covered all the PCB adhesives except for the low viscosity products and cyanoacrylate [7, 32]. Pneumatic dispensing also had this issue, where the range began from 10 000 cps, and ended at 1 000 000 cps, which provided information that almost all PCB adhesives would be processed [16, 24]. Volumetric dispensing using a pneumatic actuator had only one minus, which was that it could not process ultra-high viscosity bonding materials [16, 24]. Lastly, pneumatic jetting and volumetric dispensing using a mechanical actuator, viscosity ranges cover all adhesive materials described in Table 5.

2.2.2. Precision

The second criterion that was evaluated was precision, where scores were assigned according to the tables made in the theoretical analysis. It was important to understand that the lower the percentage was, the lower the chance and size of volume deviation would occur [7]. This change was provided in the analysis of the theoretical part, for example, if precision was ±10%, and the output would be 8mL after a certain number of cycles, it would be 8.8mL [7]. The lower scores were given to time-pressure dispensing, pad stamping, and solenoid valve jetting, which had a precision parameter from ±5% to ±10% [7, 16, 23, 33, 34, 37, 40]. This provided even more reasons for not choosing these solutions, combining their precision and viscosity range scores [7, 16, 23, 33, 34, 37, 40]. Pneumatic dispensing solution was given the score of 2, which had precision from ±3% to ±5% [16, 24]. According to the theoretical analysis, this high variation in precision was caused by the loss of vacuum inside the storage area, which created unwanted leaking [16, 24]. The same score of 2 was also given to pin-transfer dispensing, which had a precision of ±2% to ±5% [7, 32]. The change of deposited material was attributed to the pins that were used to transfer the adhesive, and after a certain number of cycles, would show a reduced „stickiness” effect [7, 32]. The score of 3 was given to pneumatic jetting, which had a precision of around ±2% [36, 39]. This was quite normal precision compared to other solutions, and would be caused by the inconsistent air pressure, which created an irregular adhesive expulsion [36, 39]. Another system that received the same score was volumetric dispensing (pneumatic actuator), which had a precision of ±1% to ±3% [25]. This indicated that the solution in cases that had a low deviation, which was mostly caused by the piston's inconsistent motion, pushed the adhesive out [25]. This would be fixed, and a lower precision would be achieved by adding some extra components or sensors that provided information about the irregular movement of the actuator [25]. Only one solution was given a grade of 4: piezoelectric jetting, which had a precision range of ±1% to ±2% [35, 41]. This was caused by the irregular movement of the piezoelectric material inside the system after a certain number of cycles [35, 41]. Although this solution had a low precision, the viscosity range was really limited, and this method was not selected for the dispensing system in this project [35, 41]. Lastly, the highest score was given to volumetric dispensing (mechanical actuator), which had the lowest precision of ±1% [25] This solution had the lowest deviation and would be caused by piston movement, which was a similar issue to the volumetric dispensing (pneumatic actuator) [25].

2.2.3. Cost

Cost was the third evaluated criterion in this area. 1 was given to the most expensive solution, and 5 was given to the cheapest. Although this evaluation was based on theoretical analysis, and cost could vary; some solutions required more components or special materials to operate. The lowest score was given to piezoelectric jetting, which required different components that worked at high speeds, which indicated that, for this solution, high-quality parts were required to operate [35, 41]. Also, the piezoelectric material was expensive, which ranged from 12 euros to 250 euros, and multiple were required; the price depended on the size of the system [78]. The lowest score was also given to volumetric dispensing (mechanical actuator). According to the research performed, the price of this solution depended on the adhesive material that was needed to extrude [28]. If the material was of a high viscosity, powerful devices such as actuators and motors were necessary; other components were also required to be of a higher grade so they would not break under high force [28]. Pneumatic jetting required a high-quality controller to perform the dispensing action [36, 39]. According to the performed analysis, the processes used compressed air to push out the adhesive through the nozzle. This required an impressive and expensive pneumatic system, especially for high viscosity material to be dispensed [36, 39]. Solenoid valve jetting operated using the magnetic force, which provided movement of the needle expensive [37, 40]. According to the analysis performed, if the system were designed from scratch, various expensive components such as magnetic actuators would be required [37, 40]. Because of these reasons, the two mentioned solutions received the scores of 2. Pin-transfer dispensing and stamping methods received a score of 3, because their price depended on the size of the tool [7, 16, 32-34]. Also, this solution would be priced higher than the multiple tools necessary if flexibility should be acquired for different parts that were processed [7, 16, 32-34]. Volumetric dispensing (pneumatic actuator) required the linear actuator to push the adhesive through the nozzle, but it also needed a pneumatic system, which provided the compressed air to the system [16, 24]. For these reasons, this solution received a score of 4. Time-pressure dispensing also required a pneumatic system to operate, and additional sensors for the timed process [7, 23]. Because of this, it received the same score as the previous solution [7, 23]. Lastly, pneumatic dispensing received the highest score making this solution the cheapest. The working principle was like the previously mentioned time-pressure dispensing [16, 24]. The only difference was that it did not require additional sensors to operate [16, 24]. These costs were evaluated, and a few key aspects were noticed that, depending on the size of the system and how many sensors and inspection devices were required, the solutions that received the scores of 4 and 5, the price could vary.

2.2.4. Complexity

The fourth criterion, which was evaluated, was complexity; it was measured according to the maintenance, difficulty of calibration, and configuration of the solution. The lowest score was given to piezoelectric jetting, because according to the research performed on this subject, these systems are complex and require a high level of education and understanding of piezoelectric components to design a system [35, 41]. Pneumatic jetting also received the same score, because the process was done at a high speed, and the compressed air to be regulated [36, 39]. The system has to be configured properly, especially when working with high viscosity adhesive, otherwise the system could be dangerous to use [36, 39]. The last non-contact dispensing method, solenoid valve jetting, received a score of 2, which also requires high speed to perform the extrusion process [37, 40]. The magnetic actuators inside need to close and open at a fast pace, which requires a highly efficient configuration [37, 40]. Maintenance is quite similar in all non-contact dispensing methods, where clogging and nozzle or plate replacement are unavoidable [35-37]. Pin-transfer and pad stamping methods received the scores of 3; the configuration of these solutions is not that difficult, only the movement has to be configured, and the geometrical code written [7, 16, 32-34]. The biggest drawback is the maintenance because everything must be cleaned manually after the process is done, each pin or the whole pad, which takes up time [7, 16, 32-34]. Volumetric dispensing using a mechanical actuator also received a score of 3, because it uses more motors in its solution, which need to be synchronized, and a better processor is needed for the controller to run software [28]. While the same method only uses a pneumatic actuator received a score of 4, because it's simpler in design [25]. It uses compressed air to complete actions, whereas in the previously mentioned method, motors are used [25]. Both systems use actuators to push the adhesive out, and the maintenance is quite similar. The storage area must be cleaned, but for the mechanical solution, the sensors should also be calibrated from time to time [28]. Lastly, the time-pressure and pneumatic received the scores of 5. Both systems work similarly; they have low complexity, and only the compressed air needs to be connected to the area from which the adhesive is extruded [7, 16, 23, 24]. Maintenance is like the methods mentioned before, where the storage area of the adhesive needs to be cleaned to prevent unwanted curing [7, 16, 23, 24].

2.2.5. Adaptability and Results

Adaptability is the final criterion that was analysed its score was based on the system's compatibility with the 3D printer platform, which includes size, extra mounting, etc. Pin-transfer and pad stamping methods received the scores of 1, because of the size needed for the tooling, and an additional space should be designed for the holding of the adhesive material [7, 16, 32-34]. It would not be enough to mount the dispenser on the old head of the 3D printer; a new area and motors should be designed to move this type of solution [7, 16, 32-34]. Pneumatic jetting would require a lot of compressed air filters because the system needs to pulse it at high pressure [36, 39]. This would take up a lot of space, limiting the movement of the head of the 3D printer, because of this, it received the score of 2 [36, 39]. The piezoelectric jetting solution is small in size, but many connections should be made, also the controller and its processor should be changed, because the system would not compute the necessary parameters for the control of this dispenser [35, 41]. While the volumetric method using the mechanical actuator would need many extra mountings and motors to operate, as in the previous solution, the controller should be changed, too [28]. Because of these reasons, they both got a score of 3. Solenoid valve jetting is not large compared to others, but an extra connection to the controller, which should control the electromagnetic forces for it to operate; for this, it received a score of 4 [37, 40]. Pneumatic and time-pressure dispensing methods both have the same adaptability; there would be a need of compress air supply system, and the head of the 3D printer should be redesigned [7, 16, 23, 24]. Volumetric dispensing using a pneumatic actuator would need a similar adaptation as the previous two solutions, and an actuator mounted [25]. Because of these reasons, the last three solutions received the scores of 5.

Summarizing the results, the pin-transfer method received a total score of 12, compared to other solutions, which really lack precision and adaptability, making the system large and not quite precise, which could affect the bead width [7, 32]. Also, because various tooling is required, it could be quite expensive to manufacture [7, 32]. Pad stamping has the same issue, but also another disadvantage is that it cannot process most of the PCB adhesives [16, 33, 34]. Because of these issues, it received a total score of 10 [16, 33, 34]. For these reasons and low adaptability, neither of the contact transfer dispensing methods will be used for this project. The non-contact dispense methods also should not be used. Piezoelectric received a total score of 12 and has two main issues: price and low ability to process PCB adhesive materials [35, 41]. The solenoid valve has the same issues, with a total score of 11; additionally, it has a low precision rating [37, 40]. While the pneumatic jetting solution has issues in other areas, the complexity and cost are big drawbacks when thinking about redesigning a 3D printer into a dispensing system [36, 39]. Time pressure dispensing had a total score of 17, but it can process high viscosity PCB adhesives [7, 23]. The volumetric method using a mechanical actuator got a total score of 17, but price and complexity are the main drawbacks why it from being chosen [28]. The pneumatic dispensing method had the highest total score of 21, but the precision difference would impact the bead width, which in turn would not meet the system requirements [16, 24]. For this reason, the volumetric dispensing method using a pneumatic actuator was chosen as the solution for this project [25]. It provided a good viscosity range, precision, cost, complexity, and adaptation balance [25].

2.3. Hardware Components Selection.

As mentioned before, during this project, a 3D printer provided by company X will be modified into an automated adhesive-dispensing system. Using SolidWorks, a 3D model was created and is shown in Fig. 10. It provides insight into the components included and helps design the changes needed to convert it into a dispensing system.

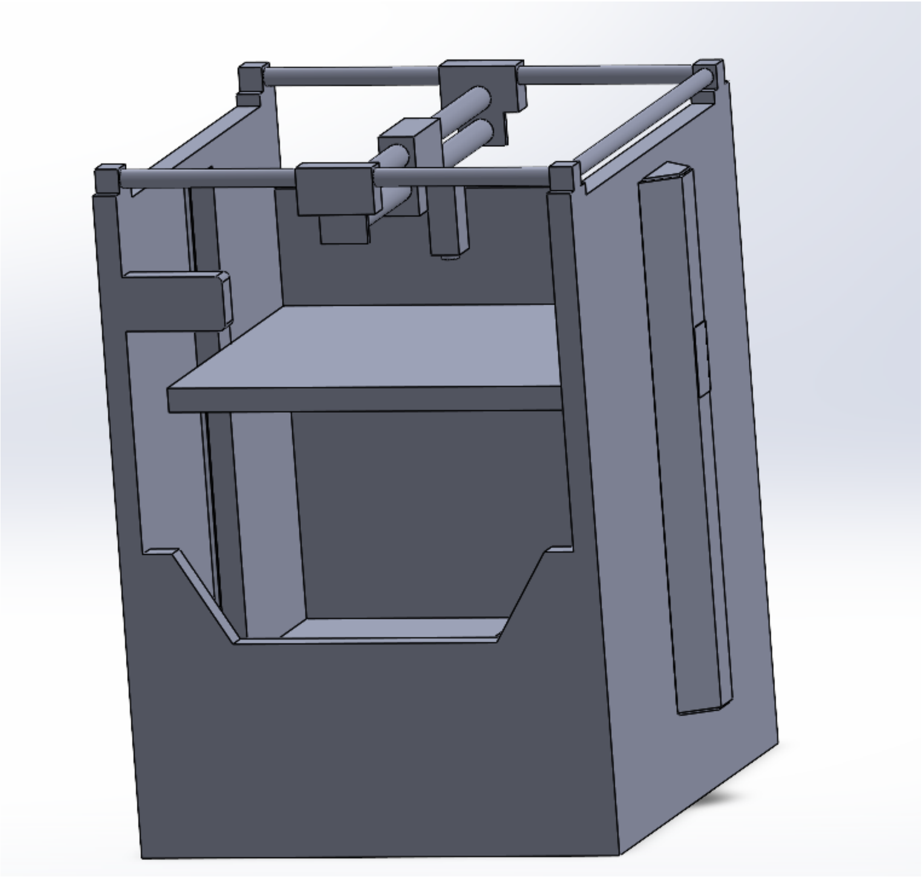


Fig. 10. 3D Model Made with SolidWorks of the 3D Printer Platform

The model shown in the figure above was made according to the system's measurements. The system used a PanelDue controller, which came with integrated firmware [79]. It had a dedicated processor board, which helped with the controls of the system [80]. Programs were made using geometrical code, which was used to provide coordinates on how the system should perform movements [80]. G-code provided a universal language that would be used for control and actions of various CNC and 3D printer devices [80]. These commands were acquired through sites like “G-code Index” or by opening the internal system config.g file, which provided insight into what command represented which action [81]. The G-codes that were used in this project were provided in Appendix 1. The movement of the system was done with the stepper motor model J-4218G2401 with belts [82]. The tool was mounted through linear motion slide blocks, which provided a smooth movement across the axes [4, 5]. The bed of the 3D printer was also mounted on these motors with the same linear motion slide blocks, which move it in the z direction [4, 5]. The system was also equipped with TCTST2103 end stop sensors, which indicated the location of the tool or the bed [83]. The power was supplied by the rsp-320-24 power block, which provided an output current of 13.4 A [84]. The wiring of the tool was run through a drag chain, which was flexible and ensured that they don’t get damaged during the movement [85].

2.3.1. Dispensing System and Block Diagram

The volumetric dispensing method with a pneumatic actuator was selected as the best option for this type of modification of the 3D printer. This type of solution performed the dispensing process with the use of a linear actuator, which pushed the adhesive material through the nozzle [25-27]. A new tool for the dispensing system had to be designed; a sketch was created to provide some insight into how the dispenser will be mounted on the platform instead of the old printing system tool, as demonstrated in Fig. 11. The design of the new components was decided upon to provide customization over the implementation decisions. The nozzle will be used from the SikaFast; this means that the mounting component had to be custom-made to hold everything in place during the dispensing process [25-27].

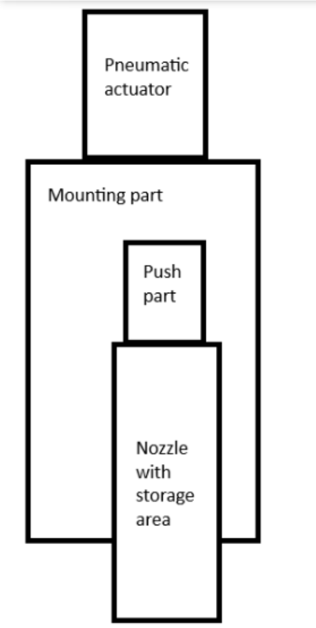


Fig. 11. Sketch of the Dispenser

The mounting part must be made to match the holes of the linear motion slides and designed to be sturdy, not creating vibrations when moving [4, 5]. It also must contain enough space for the nozzle with storage, an area component, and be tall enough to fit the push part. This mounting can be created using various materials, but 3D printing will be used, which provides the availability of customization [4, 5]. For dispensing the nozzle with a storage area, the SikaFast-5215NT was provided as an adhesive that Company X uses for its bonding process [86]. The volumetric dispensing method works perfectly with this kind of container; the system will be designed to perform the extrusion process through this component [25-27]. This adhesive has a viscosity of 16 000 cps and is a 2-part structural acrylic, which has a fast-curing time [87]. Using this component provides advantages such as no need for cleaning, because after the tank is empty, it will be replaced with a new one, and the testing can be done with a shell using another material that resembles it [87]. Also, the nozzle size sums up to around 3mm, which is the required bead width for the system [87]. The push part must be designed to fit in both holes, so measurements must be made of the SikaFast-5215NT [87]. Lastly, the linear pneumatic actuator should be chosen; in this project, the SMC CD55B40-150 will be used [88]. This device's cylinder size is 40mm, and the length of the stroke is 150mm, which is perfect for this type of system [88].

2.3.2. Pneumatic System

For the actuator to operate, certain adjustments and modifications must be made to provide compressed air for the system. Connecting the compressor to the actuator will provide no control over the system; additional components must be introduced into the solution [89, 90]. The first step is to select the right diameter pneumatic tubing, which would connect to the actuator [88]. The 6mm diameter was selected because of this reason fitting was required; the SMC KQ2H06-G01A provided the necessary connection to the actuator, and the size of 6mm [91]. Another component is required to be connected, because the actuator had two ports [88]. For the second, the SMC AN101-G01 silencer was used to "close off" the component and protected from contamination [92]. Then, through the tubing, the actuator should be connected to some sort of control device [89, 90]. For this, a pneumatic solenoid valve was used to provide power to the actuator and control the flow that reaches it [93]. The chosen model was the SVC V6110-M5-D24 pneumatic solenoid valve [93]. It had 3 ports for one of the fitting KQ2H06-M5A was used, which provided a connection to the 6mm diameter pneumatic tubing, which came from the linear actuator [94]. To port 1, the silencer SMC AN05-M5 was chosen, which "closed off" the device and provided protection from contamination [95]. To the last port 2 a fitting was selected, the SMC KQ2H10-M5A, which provided the connection of 10mm pneumatic tubing [96]. This decision was made to create a build-up of compressed air in the system, which allowed it to reach the linear pneumatic actuator instantly [89, 90]. To provide this compressed air, the system must be connected to the compressed air source, but it cannot be used directly, because it would not be "clean" [89, 90]. To make it usable, a filter must be connected to the solenoid valve and air supply system [89, 90]. For this project, the SMC AW20-F02E-B was selected as the filter of the compressed air and must be connected to the source of compressed air and the 10mm tubing, which came from the pneumatic solenoid valve [97]. The connection to the source was selected to be made through SMC KK4P-02F [98]. Lastly, a precision regulator was also selected, which would control the pressure of the system [89, 90]. For this project, the SMC AR20-F02 device was selected, which should be connected to the compressed air filter [99]. The y-connection SMC KQ2U10-02AS was connected to the compressed air filter, which provided connections to both the pneumatic solenoid valve and the compressed air regulator [100]. The regulator was also required to be connected, so fitting KQ2H10-02AS were selected to be connected on both sides [101]. To summarize everything and show how everything should be connected, a pneumatic scheme was made of the system, which was depicted in Fig. 12.

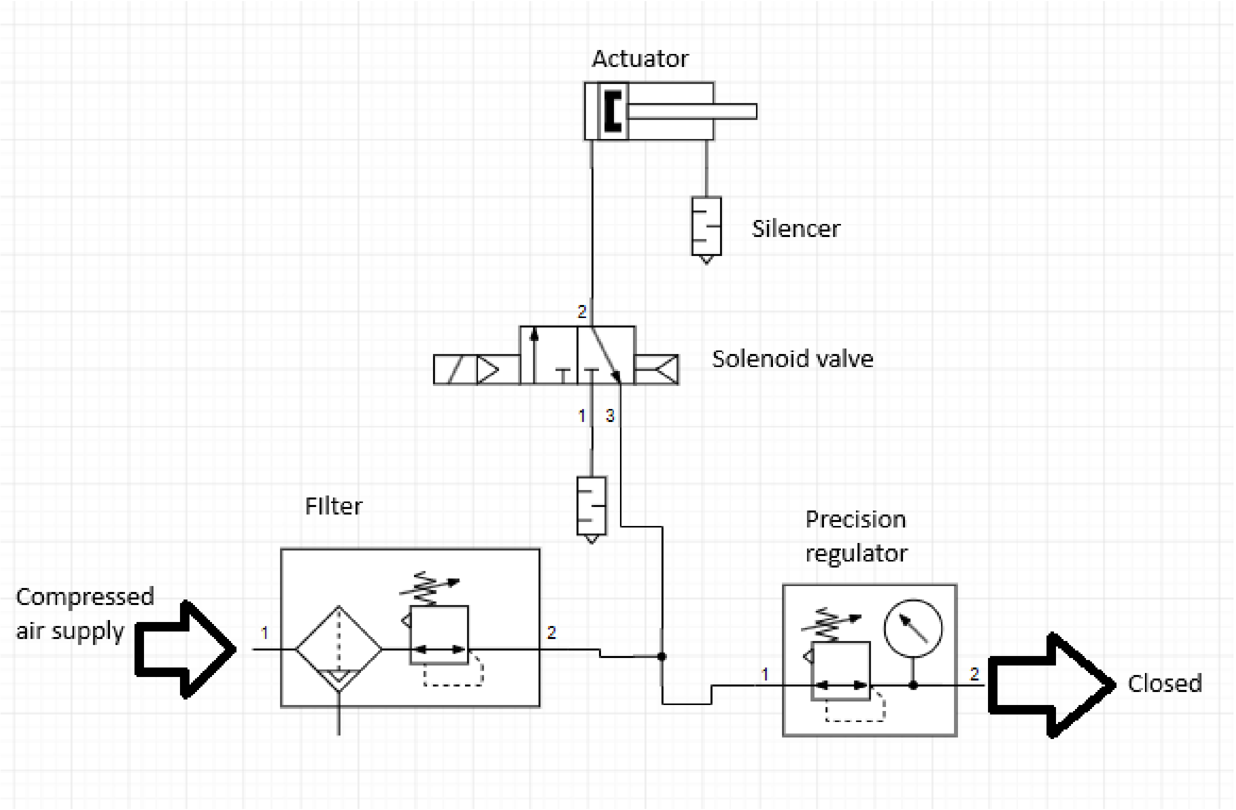


Fig. 12. Pneumatic Scheme

2.4. Chapter Summary

The requirements were determined, providing the factor by which the components should be selected. The bead width was determined as 3mm, the adhesives selected were PCB, and requirements for low precision, accuracy, and cycle time were indicated. Using the design selection matrix, the most suitable solution was selected, which was the volumetric dispensing using a pneumatic actuator. This method provides many advantages, such as low precision, complexity, and low cost. The existing 3D printer platform was analysed, which provided information on the already existing components. The selection of how the dispenser should be designed was made, the adhesive material was identified, and the actuator was selected. For the operation of the linear actuator, a pneumatic system was necessary, whose components were selected, and a pneumatic scheme was drawn that provided information on how everything should be connected.

3. Dispensing System Based on a 3D Printer Platform

Company X received a project to create an adhesive dispensing system, which would be used for bonding the two components, demonstrated in Fig. 13. Because the bottom components on which the adhesive should be extruded, using the standard manufactured automated dispensing system would be an expensive choice. For this reason, the 3D printer platform reconstruction was chosen, because the device already provided the movement in the x, y, and z axes, and the firmware had the necessary understanding of geometrical code to create programs, which would follow the dispensing path. The components provided below were implemented as electronic device screens; for this reason, PCB adhesives were used in the process to maintain the integrity necessary for these kinds of devices. The bottom part of the bonding width was 3mm; the nozzle was chosen to be around the same diameter to provide a consistent dispensing line.

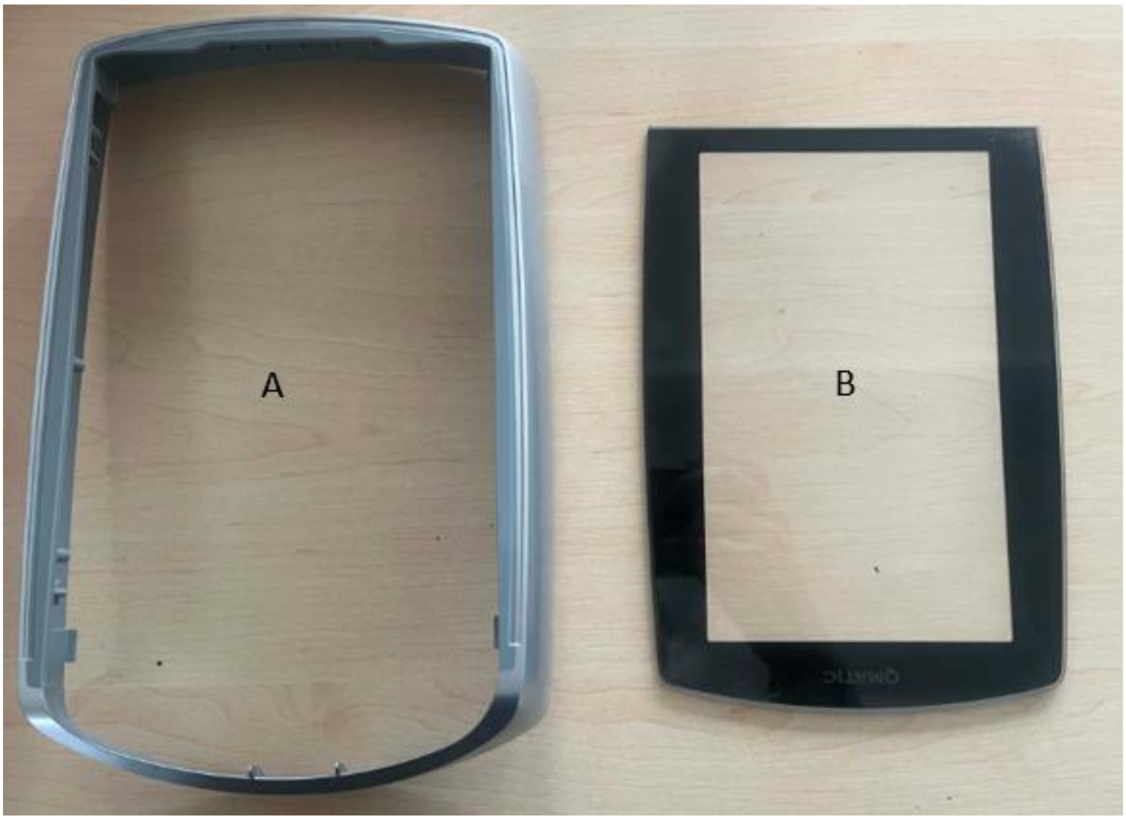


Fig. 13. Provided Components, A – Bottom Part; B – Top Part

Company X provided a custom-made printer, which, after years of use, began to show inaccuracies in the process. The platform provided movement of the x and y axes, with the mounted stepper motor model J-4218G240 with belts, and the plate mounted to the motors provided the movement in the z direction. The system ran a PanelDue controller with the same firmware; these components were not modified because they provided fitting actions for the dispensing system. The solution chosen for this project was the volumetric dispensing, using a pneumatic actuator. This selection provided less complexity, lower cost, and lower maintenance than other methods. This solution had two different approaches using either a pneumatic or a mechanical actuator, which was not chosen, because of the complexity, requirement of multiple components to act, and the high cost. Before the assembly and designing steps were performed, the existing 3D platform was measured, holes for mounting were determined, and a working area was identified. This determined what components should be assembled to create a flexible system, which processed the components and provided availability for the use of different parts. This also provided an insight into which components were purchased and which were designed and printed. Based on the pneumatic system and the necessary components determined in the previous chapter, a bill of materials was created for easy navigation and is shown in Table 7. This table was provided to Company X as a list of necessary components for the assembly of the dispensing system.

Table 7. Bill of Materials

No.	Description	Buy/make	Quantity	Notes
1.	SikaFast-5215NT	buy	1	The chosen adhesive material, which was used for testing and the process, also has an incorporated nozzle.
2.	Mounting component	make	1	Designed according to the measurements of the linear pneumatic actuator, the SikaFast shell, and the existing mounting ports of the platform. To be used as a holding part for all dispensing components.
3.	Push component	make	1	Designed to fit into the SikaFast shell and act as an intermediate between the adhesive and the linear actuator.
4.	Base part holding component	make	1	Designed according to the measurements of the bottom part of the processed component to provide a location where the processing was performed.
5.	Linear actuator SMC CD55B40-150	buy	1	Used for the dispensing process to push the intermediate part through the nozzle, mounted on the dispenser.
6.	Pneumatic solenoid valve SVC V6110-M5-D24	buy	1	Used to control the compressed air source for the linear actuator to prevent constant pressure and provide control.
7.	Compressed air filter SMC AW20-F02E-B	buy	1	Used for cleaning compressed air, which is provided by the source, to avoid contaminants in the system.
8.	Compressed air regulator SMC AR20-F02	buy	1	Used to maintain a stable air pressure in the system, to ensure proper working of the solenoid valve.
9.	Silencer SMC AN101-G01	buy	1	Used to “close off” one port of the pneumatic linear actuator to reduce noise and prevent contamination.
10.	Fitting SMC KQ2H06-G01A	buy	1	Used for the port of the pneumatic linear actuator to provide a connection to 6mm tubing.

No.	Description	Buy/make	Quantity	Notes
11.	Pneumatic tubbing 6mm	buy	2m	Used to connect the pneumatic linear actuator to the pneumatic solenoid valve.
12.	Fitting KQ2H06-M5A	buy	1	Used for the 2-port pneumatic solenoid valve for connection of 6mm pneumatic tubing.
13.	Silencer SMC AN05-M5	buy	1	Used for the 1-port pneumatic solenoid valve to "close off" and prevent contamination.
14.	Pneumatic tubbing 10mm	buy	6m	Used for connecting the pneumatic solenoid valve to the compressed air filter. Connect the compressed air filter to the compressed air regulator.
15.	Fitting SMC KQ2H06-M5A	buy	1	Used for the 3-port pneumatic solenoid valve to be connected to the 10mm pneumatic tubing.
16.	Y-fitting SMC KQ2U10-02AS	buy	1	Used for connecting the compressed air filter to the compressed air regulator and the pneumatic solenoid valve through 10mm pneumatic tubing.
17.	Connection SMC KK4P-02F	buy	1	Used for connecting the compressed air filter to the compressed air source.
18.	Fitting KQ2H10-02AS	buy	2	Used for connecting the compressed air regulator to 10mm pneumatic tubing from both sides.
19.	Mounting bracket SMC AW23P-270AS	buy	1	Used for mounting the compressed air filter.
20.	Mounting bracket SMC AR23P-270AS	buy	1	Used for mounting the compressed air regulator.

The components chosen were according to the research performed in the previous chapter and the system requirements. The SikaFast-5215NT had a nozzle diameter of 3mm, which is the necessary bead width, and the length of the linear actuators was enough to provide the necessary push to extrude the material through the design of the adhesive materials' holding shell. All the components of the pneumatic system had to be connected and mounted on the platform; they were selected according to the analysis performed on this type of solution. After the components were determined, the design stage began.

3.1. 3D Printer Platform Modifications

For modifications to begin, steps were taken that ensured that the implemented components would work and assemble correctly. The 3D printer platform tool was removed, and the mounting area was measured to identify which connections need to be designed on the new mounting component. The printing and designing of certain components were selected to provide the customization needed for the mounting, push, and holding parts. Firstly, the mounting part was designed as a 3D model, which was then printed. The component was required to be able to hold the SikaFast and the pneumatic linear actuator SMC CD55B40-150. The SikaFast 5215-NT was provided by Company X, and measurements were made to identify the space needed for the mount, which should hold it in a steady position. The height of this product is around 156 mm, and the diameter of the larger hole is around 56 mm. Also, there is an extruded line feature on the bottom of the shell, which was around 10 mm wide. The top was designed to fit the SMC CD55B40-150 linear pneumatic actuator; after that, holes for mounting to the linear motion slide were measured. The 3D model of this part was made using SolidWorks and is demonstrated in Fig. 14.

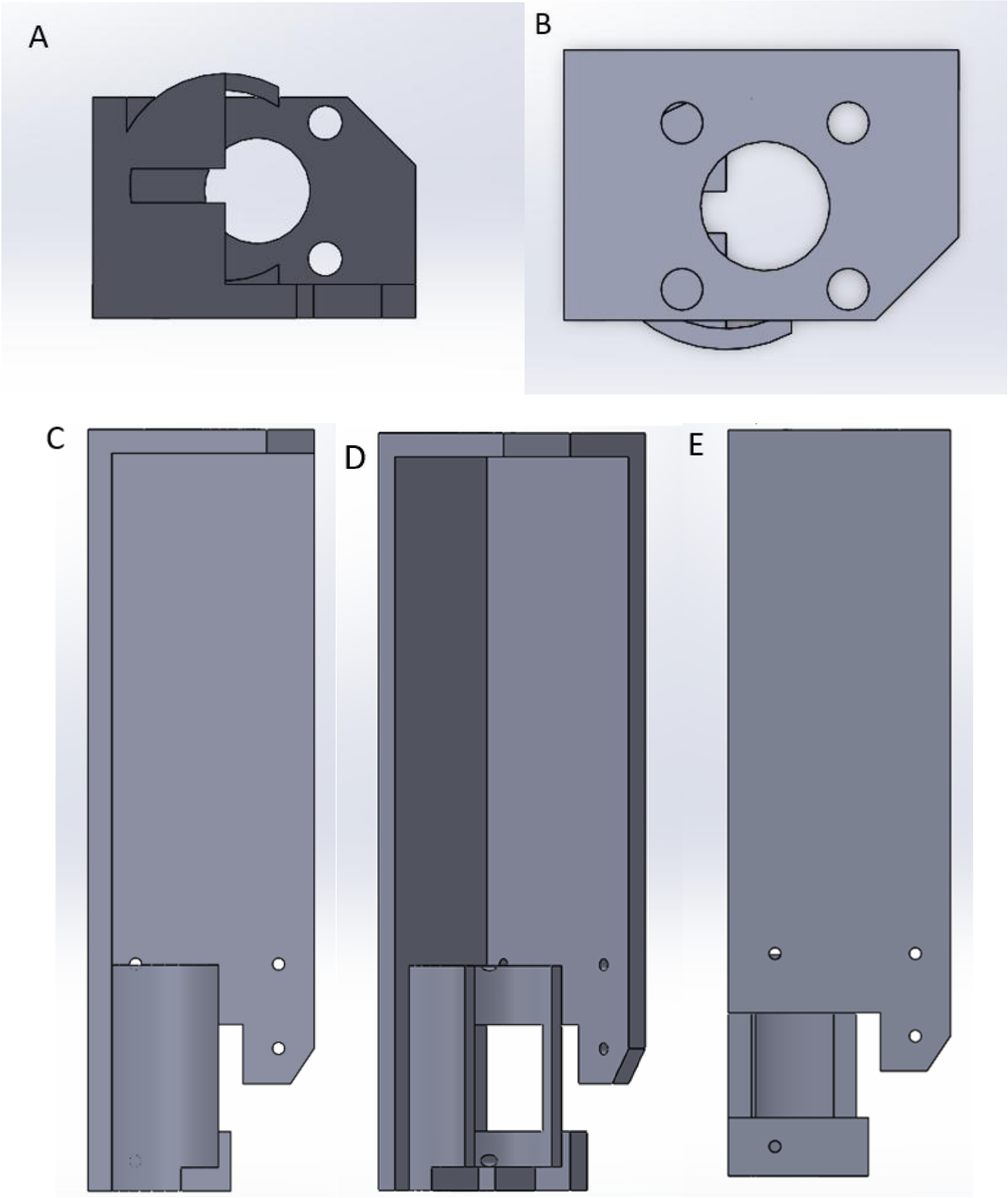
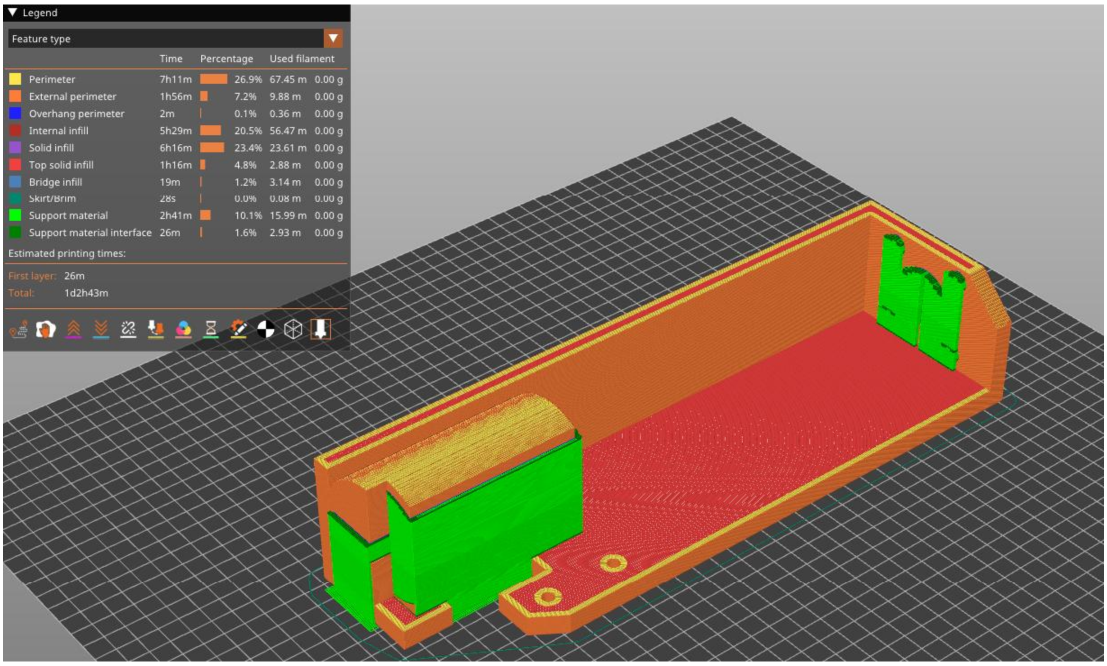


Fig. 14. 3D Model of the Mount Part Created Using SolidWorks, A – Bottom View; B – Top View; C- Left Side View; D – Diagonal Front View; E – Back View

The height of the mounting was made to be 306 mm to make room for the SikaFast 5215-NT shell, which is 156 mm, and the SMC linear actuator piston length, which was 150 mm. On top of the mounting, the hole in the middle had a diameter of 31.5 mm, which helped the piston extrude without collision, and an extra 0.5mm was added for the printing process, because the printed plastic, in some cases, shrinks. The 4 smaller holes were designed for mounting the actuator, and the screws that go into them had a diameter of 10mm, so the space was created at 10.5 mm, with some extra size for the same reason. On the side, there was some space left that could be seen through. Its purpose was to avoid collision with the linear motion slide and the belt. The 4 holes on the side were made for mounting purposes, and the diameters were made to be 5.5 mm. They attach to the linear motor slide through screws, which were removed from the old 3D printer tool. The holding area of the mounting part was designed to hold the SikaFast shell according to the measurements made. The diameter of the hole was 57 mm to create space to insert it and remove it when needed. All the walls of the mounting component were made to be 10mm for sturdiness to hold the components that will be assembled to it. Then this model was tested through Prusa Slicer to see if it's possible to print. The results are shown in Fig. 15.


Legend

Feature type

		Time	Percentage	Used filament	
🟨	Perimeter	7h11m	26.9%	67.45 m	0.00 g
🟧	External perimeter	1h56m	7.2%	9.88 m	0.00 g
🟦	Overhang perimeter	2m	0.1%	0.36 m	0.00 g
🟥	Internal infill	5h29m	20.5%	56.47 m	0.00 g
🟪	Solid infill	6h16m	23.4%	23.61 m	0.00 g
🟥	Top solid infill	1h16m	4.8%	2.88 m	0.00 g
🟦	Bridge infill	19m	1.2%	3.14 m	0.00 g
🟩	Skirt/Brim	28s	0.0%	0.08 m	0.00 g
🟩	Support material	2h41m	10.1%	15.99 m	0.00 g
🟩	Support material interface	26m	1.6%	2.93 m	0.00 g

Estimated printing times:

First layer: 26m
Total: 1d2h43m

Fig. 15. Prusa Slicer Analysis of the Designed Mounting Component

For the settings, the supports were turned on, because of the complex structure of the components, they were needed for the successful printing process. The first and final layers were increased, and full fill was selected. This analysis proved that the designed 3D model was possible to print. This step was necessary to make sure that the 3D model provided to Company X would not create any difficulties during the printing process. After this testing was conducted, the model was sent to Company X for further printing.

The push part was the second designed component; it was necessary because the beam of the SMC CD55B40-150 linear pneumatic actuator only had a circular form, which was not suitable for the SikaFast adhesive shell. An intermediate part was needed, so the design of the push part was decided upon to provide the necessary pushing capabilities needed for the dispensing process. This component was designed to fit into the SikaFast shell holes, which were measured, and the height of this component was designed so that it could fit when the SikaFast was filled with the adhesive. Additionally, a request was made for further adaptation of sensors, which would measure the amount of material inside the SikaFast or provide information about the temperature of the adhesive. A design was created using SolidWorks, and the 3D model was depicted in Fig. 16.

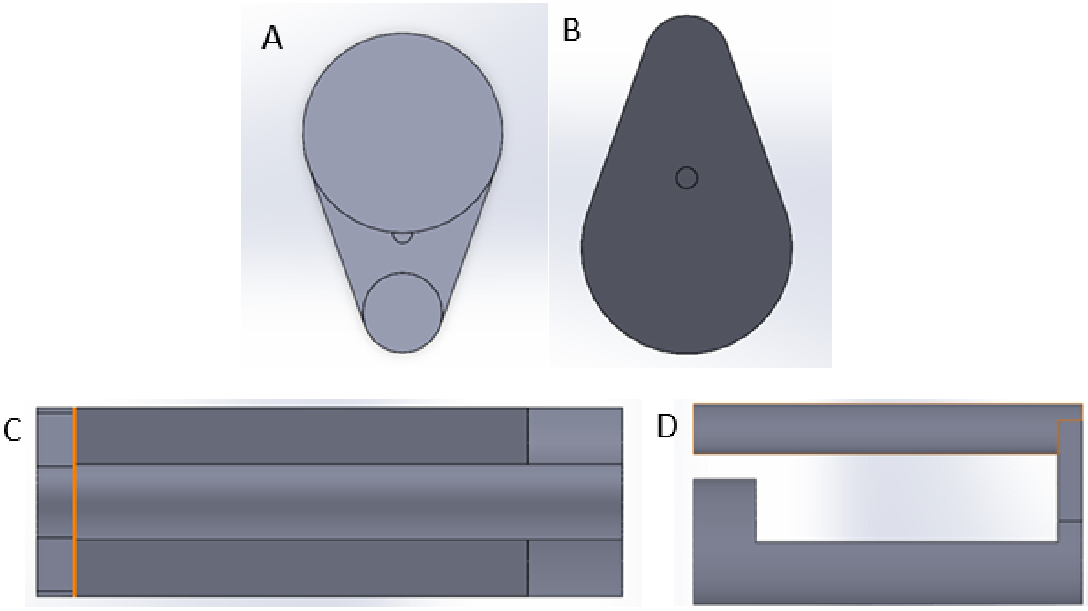
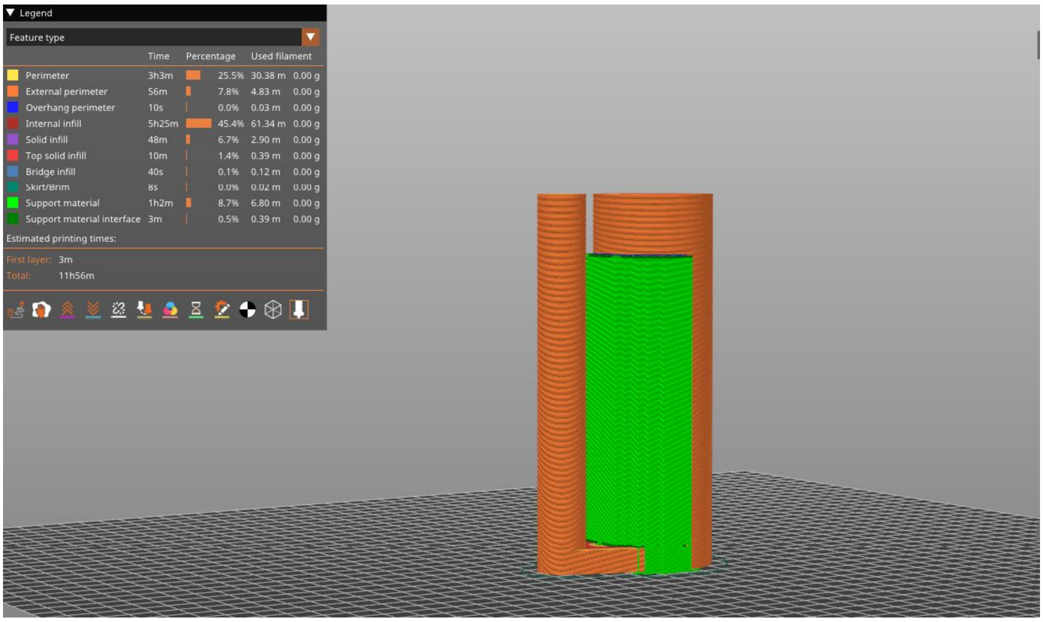


Fig. 16. Push Part Design Made Using SolidWorks, A – Top View; B – Bottom View; C – Sideview Front; D – Side View

Both circles were created according to the SikaFast component measurements, and the length was made to fit the whole shell and be suitable for the designed mounting component. The final height of the component was 166 mm; an additional 10 mm was added to create the support area, which was designed to sit on top of the shell. The bigger circle's diameter was 50.5 mm, and the smaller 20.5 mm, with an additional 0.5 mm to avoid shrinkage during the printing process and to avoid the part being too big to fit into the shell. The hollow part was designed for the future introduction of a sensor. Using Prusa Slicer, the same analysis was performed on the push part and can be seen in Fig. 17.



		Time	Percentage		Used filament	
🟨	Perimeter	3h3m		25.5%	30.38 m	0.00 g
🟧	External perimeter	56m		7.8%	4.83 m	0.00 g
🟦	Overhang perimeter	10s		0.0%	0.03 m	0.00 g
🟥	Internal infill	5h25m		45.4%	61.34 m	0.00 g
🟪	Solid infill	48m		6.7%	2.90 m	0.00 g
🟥	Top solid infill	10m		1.4%	0.39 m	0.00 g
🟦	Bridge infill	40s		0.1%	0.12 m	0.00 g
🟩	Skirt/Brim	8s		0.0%	0.02 m	0.00 g
🟩	Support material	1h2m		8.7%	6.80 m	0.00 g
🟩	Support material interface	3m		0.5%	0.39 m	0.00 g

Estimated printing times:

First layer: 3m
Total: 11h56m

Fig. 17. Prusa Slicer Analyses of the Designed Push Component

The Pruse Slicer analysis performed similarly to the mounting component, providing information on whether it can be printed. Settings such as the support were selected to provide the necessary information about the areas where hang was avoided. After the component was analysed and designed, the 3D model was sent to Company X for further printing.

Lastly, a base part holding component was designed, which was used to provide information for the system on where the dispensing process should occur. The bottom part of Fig. 13. was measured to make sure that this part will be held inside the designed component. Also, the bed of the 3D printer's platform had holes; this was the area where the designed component was mounted. After these measurements were made, a 3D model was made using SolidWorks, depicted in Fig. 18.

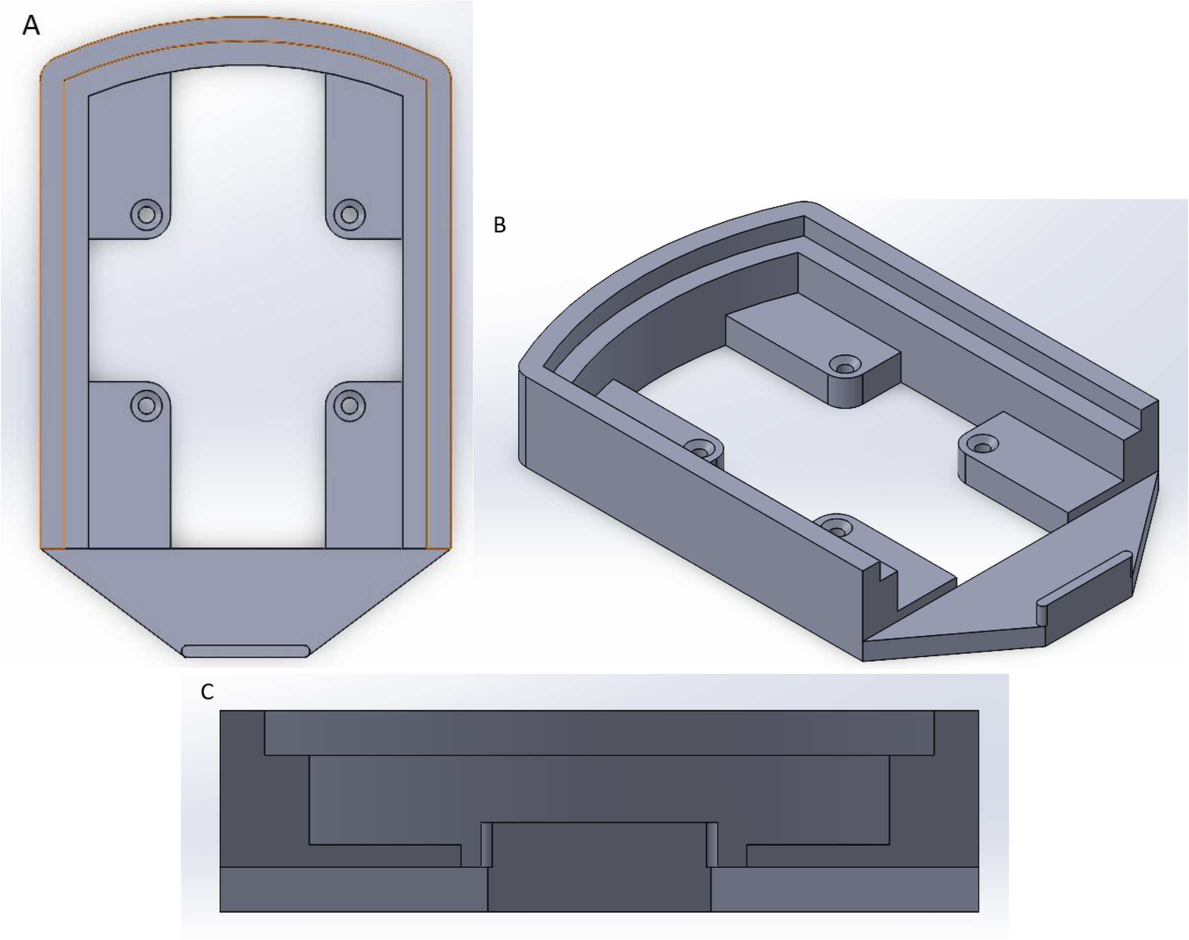
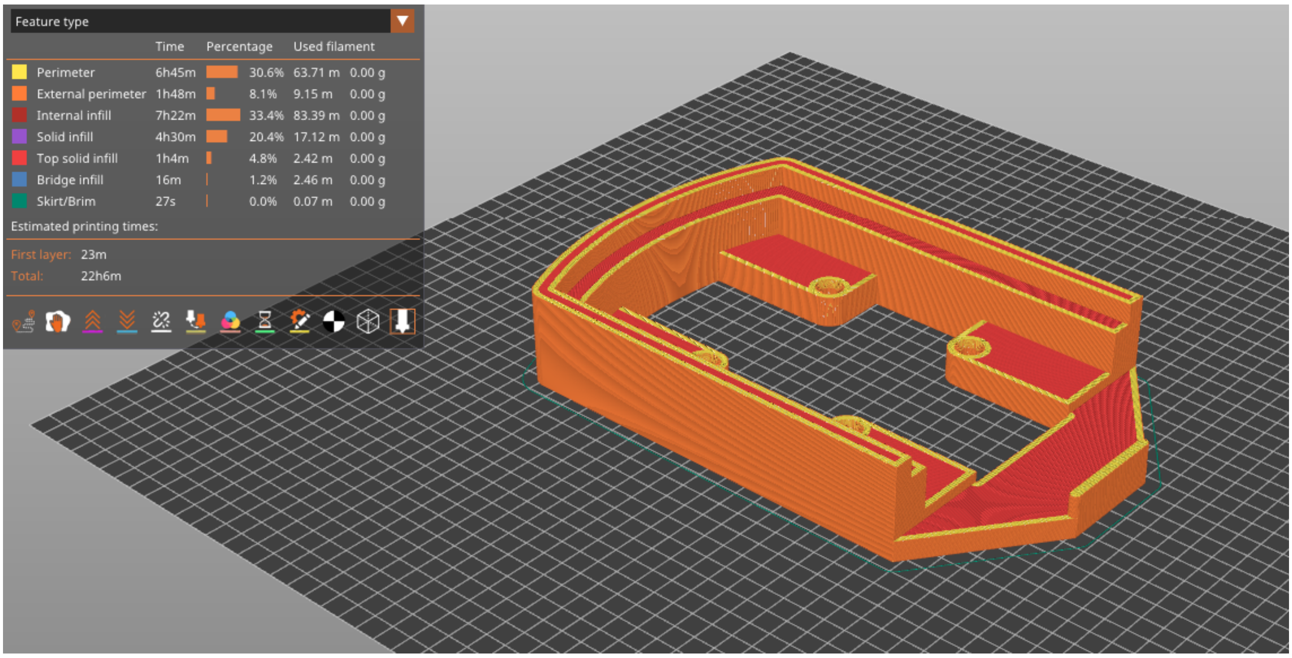


Fig. 18. Base Part Holding Component Made Using SolidWorks, A – Top View; B – Diagonal View; C – Side View

The component that was provided in the figure above was made to fit the bottom part, where the dispensing process will occur. It was measured, which provided information on how the design was made, the area was created in a way which provided space for removal and placement, and reduced any movement that was caused by the system. The length of the part that was fitted into the designed part was 245mm, and the width was 145mm. According to these measurements, the design was made with the top fitting area, which was at a 45 ° angle and a length of 170mm. The height of the designed components at the highest point was 50mm, but another lower wall was also designed at a height of 40mm, with a 10mm distance from the higher wall. This was decided upon to create an area for the component to rest upon. At the bottom, four areas dedicated to mounting on the platform's plate were designed, with spaces in between, which reduced the material used during the printing process. The holes were designed to be 100mm apart from left to right, and 110mm apart from top to bottom. This was made according to the measurements of the 3D printer platform's plate. The holes were made to be 10.5mm, with an extra 0.5mm for the printing error. At the bottom of the design, an extruded edge was made, with a width of 45mm and a length of 5mm. This was created to hold the bottom part in place during the dispensing process, and it was raised 10mm. Like the previous designs, a Prusa Slicer analysis was performed, which provided information on whether the component can be printed and was depicted in Fig. 19.



Feature type

		Time	Percentage	Used filament	
🟨	Perimeter	6h45m	30.6%	63.71 m	0.00 g
🟧	External perimeter	1h48m	8.1%	9.15 m	0.00 g
🟥	Internal infill	7h22m	33.4%	83.39 m	0.00 g
🟪	Solid infill	4h30m	20.4%	17.12 m	0.00 g
🟥	Top solid infill	1h4m	4.8%	2.42 m	0.00 g
🟦	Bridge infill	16m	1.2%	2.46 m	0.00 g
🟩	Skirt/Brim	27s	0.0%	0.07 m	0.00 g

Estimated printing times:

First layer: 23m

Total: 22h6m

Fig. 19. Prusa Slicer Analyses of the Designed Base Part Holding Component

Because this component did not have any complex parts, a support option was not needed. Similar settings in other areas were selected as in the previous designs. After the analysis was performed, the 3D model was sent to Company X for further printing.

3.1.1. System Assembly

After all the 3D models were all the models were designed, they were produced by Company X, which used an FDM 3D printing device. The first component provided was the mounting part, which was depicted in Fig. 20. It was then mounted to check if the holes matched the linear motion slide; one hole was made too high. This issue was solved by mounting the component on the steel plate of the linear motion slide. Then, through screws which had a 5mm diameter, the part was mounted. The linear actuator was then assembled on top of the mounting component. 10mm diameter screws were used to mount it on top of the printed part. Then the middle area was checked to see if the beam of the linear actuator has enough space to extrude when compressed air is provided. The SikaFast was tested to see if it fits inside the designed area, which provided enough room to sit inside, without any movement, and to be removed when it was necessary. Some damage was noticed on the printed component; this was caused during the FDM 3D printing process, where plastic was not extruded correctly. This was a common issue, especially in more complex components, but the structure of the final product was not affected.

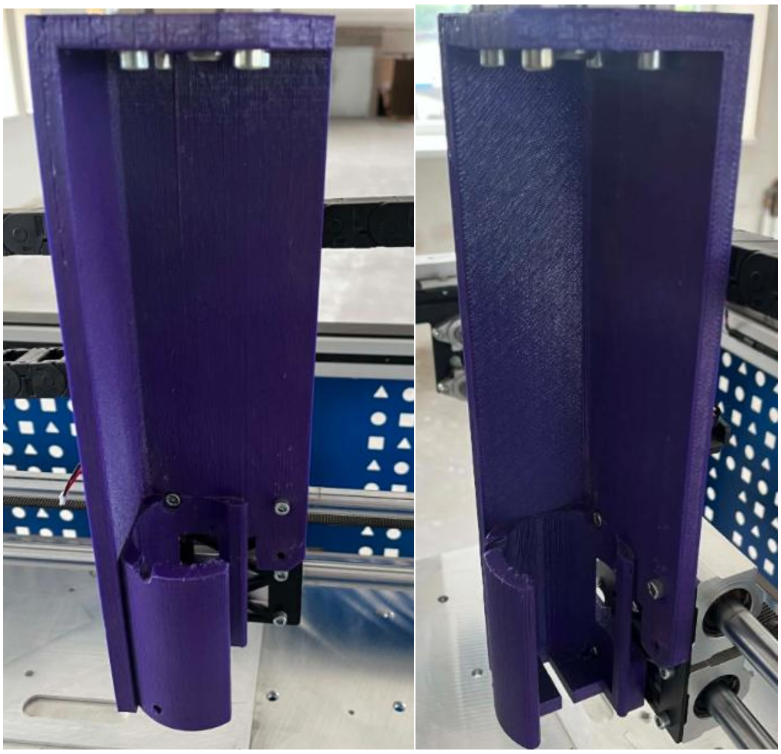


Fig. 20. Printed Mounting Part Assembled to the System

The push part was also produced using the same FDM 3D printing device. And the result was depicted in Fig. 21. When the part was received, testing was performed to see if it fitted inside the SikaFast shell. And if the designed height of the component was enough to be easily removed and placed in the system if needed.

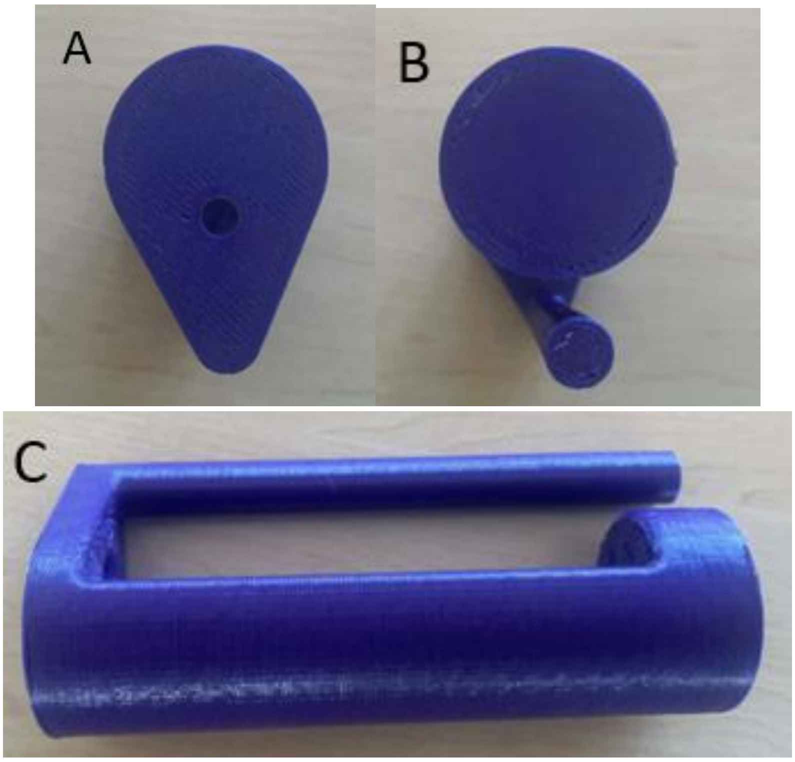


Fig. 21. Printed Push Part, A – Top View; B – Bottom View; C – Side View

The holding component was also produced with the FDM 3D printing device and was depicted in Fig. 22. Two holes in diagonal spaces were used for mounting to the platform plate two screws were drilled to produce a movable component. After it was assembled to the plate, it was tested with the component on which the dispensing process will occur. It provided stability, which was needed to extrude an accurate adhesive line. Also, the part was removed and placed easily. This component provided the necessary location parameters for further steps.

Fig. 22. Holding Component Printed and Mounted

After these components were printed and tested, the pneumatic system was assembled according to the scheme, which was created during methodological analysis. All components were provided from the BOM by Company X. The first step that was performed was the component assembly of the linear pneumatic SMC CD55B40-150 actuator. This device was already mounted to the printed component. In the bottom port, the SMC AN101-G01 silencer was fitted, which prevented contamination and noise. Then, into the top port, the SMC KQ2H06-G01A fitting was inserted, which supplied compressed air through pneumatic tubing of 6mm diameter. This 6mm tubing was cut according to the length needed to connect to the solenoid valve. It was then connected to the SMC KQ2H06-G01A fitting and was run through the drag chain into the bottom of the platform.

The solenoid valve was mounted on the bottom part of the platform in proximity to the controller's processor board. Four holes were drilled, and the pneumatic solenoid valve SVC V6110-M5-D24 was assembled into the system, which was depicted in Fig. 23. A part. The KQ2H06-M5A fitting was assembled to port 2 of the device, and the 6mm tubing, which came from the pneumatic linear actuator, was connected. The SMC AN05-M5 silencer was assembled to port 1, which prevented contamination of the device. Into port 3, the SMC KQ2H06-M5A fitting was connected to provide the compressed air from other pneumatic system devices through a 10mm pneumatic tubing. Then the pneumatic solenoid valve was connected to the controller's processor board depicted in the Fig. 23. B part with a red circle. The connection was made using the red and black + and – wires to the fan port 0, which provided information for the further steps.

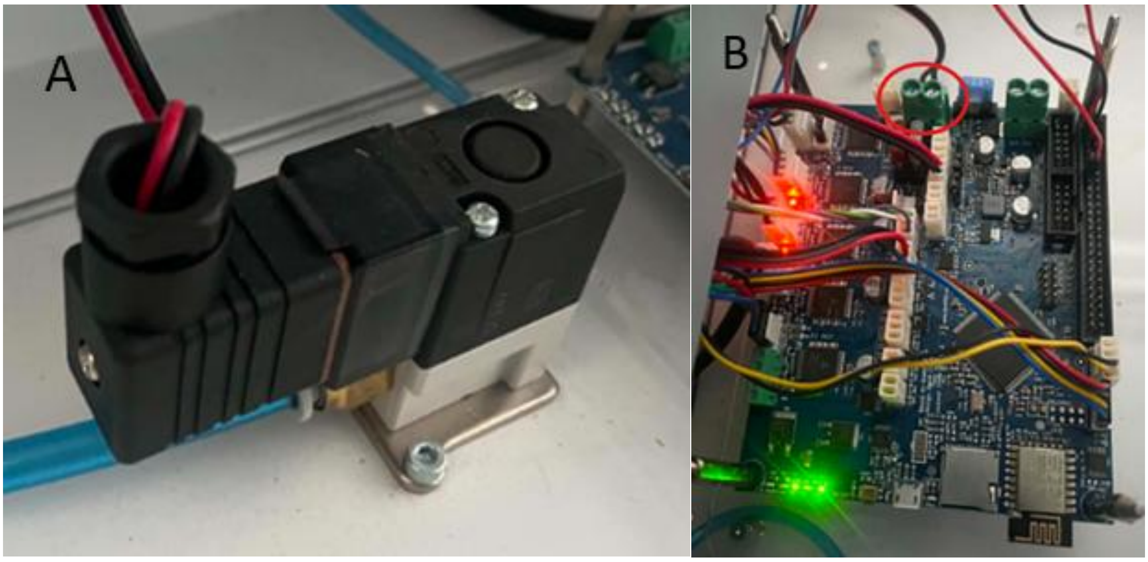


Fig. 23. A – Assembled Pneumatic Solenoid Valve; B – Pneumatic Solenoid Valve Connection to the Controller's Processor Board Marked with the Red Circle

Through the pneumatic tubing of 10mm, the solenoid valve was connected to the compressed air filter SMC AW20-F02E-B, which was depicted in Fig. 24. A part. Another component, the Compressed air regulator SMC AR20-F02, was also assembled into the system and was depicted in Fig. 24 B part.

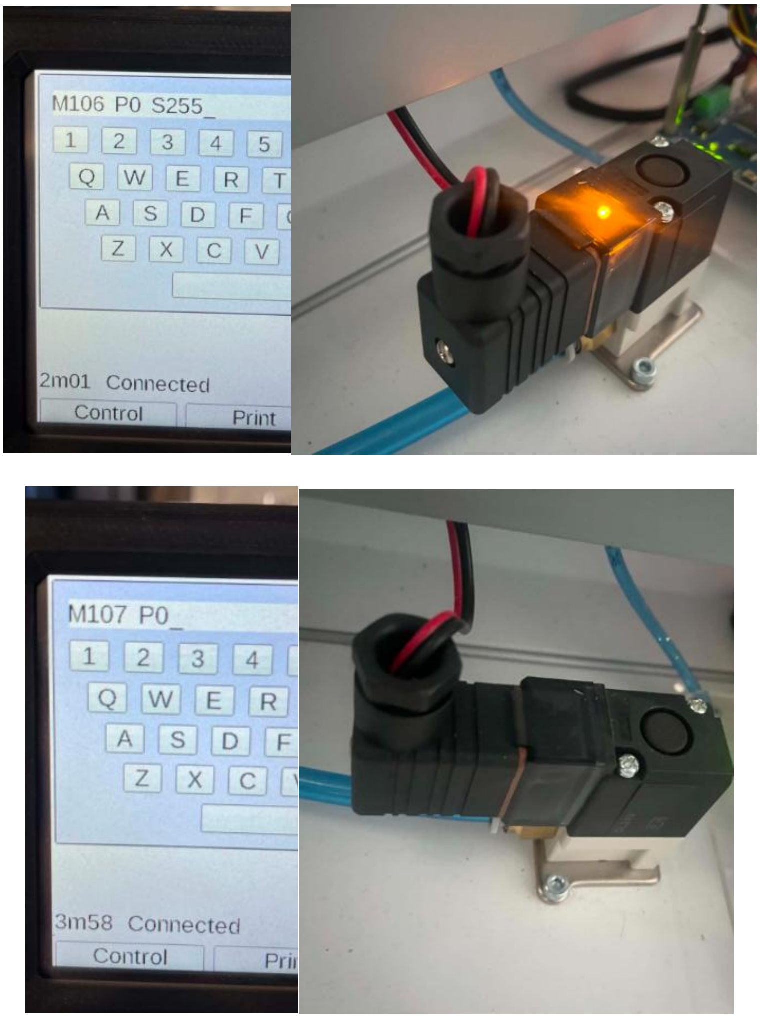
Fig. 24. A – Compressed Air Filter; B – Compressed Air Regulator

The compressed air filter SMC AW20-F02E-B was mounted on the platform using the SMC AW23P-270AS bracket. The SMC KQ2U10-02AS y-fitting was connected to the right, which provided a connection to the pneumatic solenoid valve and the SMC AR20-F02 compressed air regulator. There were holes made in the platform to reduce the distance of the 10mm pneumatic tubing needed to connect to these components. On the left, the SMC KK4P-02F connection was assembled to connect the system to the compressed air supply. This device was used to filter the air that came from the supply to prevent any contaminants that could travel into the system. The SMC AR20-F02 compressed air regulator was mounted to the platform using the SMC AR23P-270AS bracket. On both sides, the KQ2H10-02AS fittings were connected to provide the pneumatic tubing of 10mm connection that came from the compressed air filter. On the other side, the fitting provided a closing to the system, but because accurate attachments were not selected, it was closed off with a zip tie and the 10mm pneumatic tubing, which provided a temporary solution. This device was used to contain pressure in the system. After everything was assembled, the dispensing tool was achieved and demonstrated in Fig. 25. This provided the necessary structure for the next testing and calibration stage.

Fig. 25. Assembled Dispenser

3.2. Calibration of the System

After the dispenser and pneumatic system were assembled, calibration was done to verify if the components work properly. When the custom-made 3D printer was provided, it had some accuracy issues, which were solved. For this step, the geometrical code was used, which was entered through the command option on the PanelDue controller. As mentioned in the methodological part of this project, the necessary commands were given in Appendix 1. Firstly, the solenoid valves' opening and closing were tested, because it was connected to the fan port 0 in the controller's board, the code to turn on the valve was M106 P0 S255. The click sound was heard, and the light on the solenoid valve turned on. For turning off the device, code M107 P0 was used, and it closed completely. The successful actions can be seen in Fig. 26. The solenoid valve should be turned on at 100% power, because it provided compressed air to the SMC CD55B40-150 actuator.



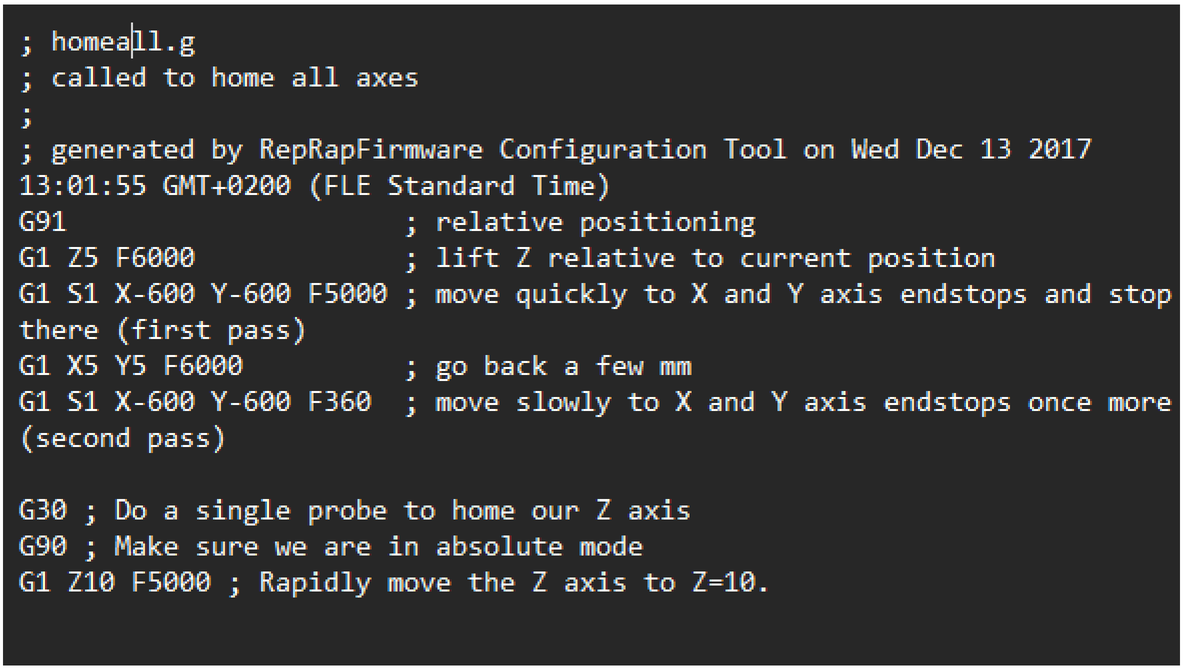
```
M106 P0 S255_
```

```
M107 P0_
```

Fig. 26. Test Performed for the Solenoid Valve

After the solenoid valve was tested, the movement of the system was adjusted to perform accurate steps in the x, y, and z axes. Firstly, the distance that the assembled head travelled was evaluated through the controller by using the buttons to move certain axes. A ruler was used to determine if the tool moved 10 mm when the button that indicated that was pressed; the results for axes came back positive. This meant that the commands were set correctly for the movement to be done according to the provided distance. But another issue was noticed, when pressing the home button, it was not moving to the 0 position, and the motors tried to push the dispenser tool to the side. This meant that when programs were created, manual adjustments needed to be made, which created temporary 0 positions. This was a flawed solution because you cannot manually move the dispenser into the same position each time. This created issues, especially when the bonding component is placed in the holding part, which was mounted on the bed of the platform. The home button was required to be fixed to provide a flexible flow of the process. This button was regulated through the homeall.g file, which determined the settings of how that button performs. Also, the config.g file was adjusted to implement commands necessary for the dispensing process.

The operation area was lowered in the config.g file, in the hopes that this would fix the issue of the dispensing tool going to the side and not stopping. The old values of M208 were altered from minimum M208 X-300 Y-300 and maximum M208 X300 Y300 to M208 X-280 Y-270 for the minimum and M208 X280 Y270 for the maximum. This setting provided information to the system on how much it can move in the x and y axes. This fix did not provide a good result; the error still occurred, and then the end stop sensors were tested if they were operational. Through the controller, the command M119 was used to check if the positions of the axes were registered. This provided information that these sensors performed the actions. This meant that the base files of config.g and homeall.g had to be altered. The old homeall.g files code was demonstrated in Fig. 27.

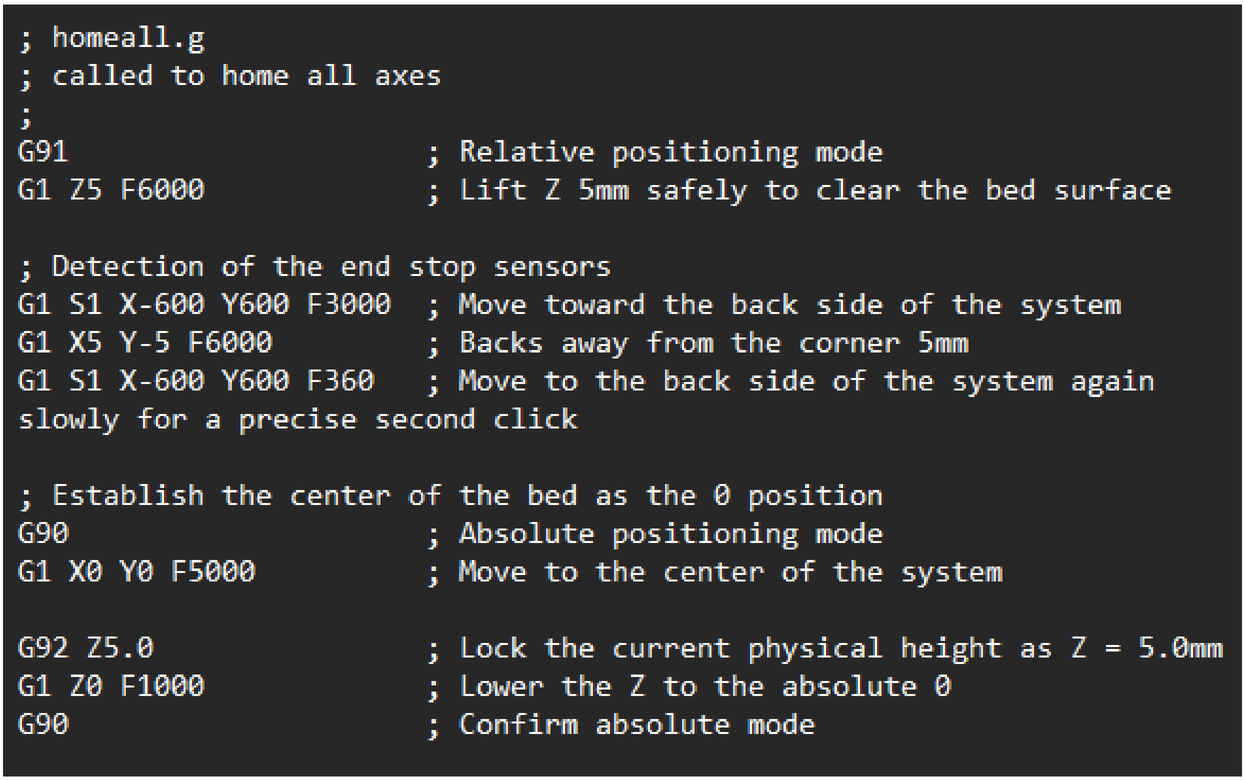


```
; homeall.g
; called to home all axes
;
; generated by RepRapFirmware Configuration Tool on Wed Dec 13 2017
13:01:55 GMT+0200 (FLE Standard Time)
G91                     ; relative positioning
G1 Z5 F6000             ; lift Z relative to current position
G1 S1 X-600 Y-600 F5000 ; move quickly to X and Y axis endstops and stop
there (first pass)
G1 X5 Y5 F6000          ; go back a few mm
G1 S1 X-600 Y-600 F360  ; move slowly to X and Y axis endstops once more
(second pass)

G30 ; Do a single probe to home our Z axis
G90 ; Make sure we are in absolute mode
G1 Z10 F5000 ; Rapidly move the Z axis to Z=10.
```

Fig. 27. The Geometrical Code of The Original Homeall.g File

This program was created in 2017 and provided the system steps to take the current position as the relative one, which meant that it took 0 positions at the current one. The Z axis was then moved 5mm in the positive direction at 100 mm/s. Then the x and y axes moved 600mm in the negative direction, and S1 indicated that when the end stop sensors detected the tool. This was the area where the tool was hitting the side of the system. The end stop sensors did not locate the location of the tool. Also, this file provided the location 0 at the corner; for this system, the idea was to provide 0 in the middle of the system, which reduced the cycle time.

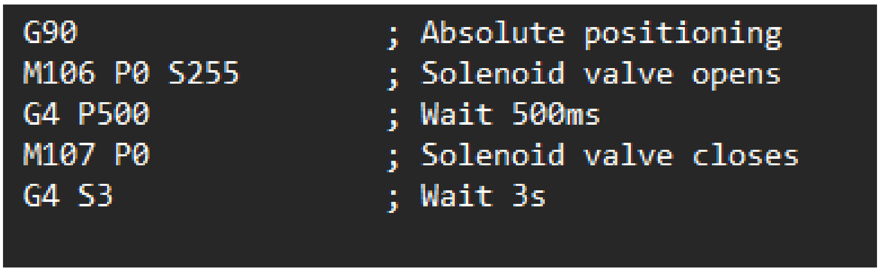
This file was also altered, and the config.g file was altered from M574 X1 Y1 S1 to M574 X1 Y2 S1. This was changed because the end stop sensor was mounted at the left back corner of the system. It identified the parameters of the axes and provided how the system should operate, and the change was made from Y minimum to Y maximum because now the home button goes to the top. The altered homeall.g code was demonstrated in Fig. 28. The first modification, which was made instead of the tool traveling on the Y axis to the negative it was changed to go to the positive. This meant that when the home button was pressed, it traveled to the top left corner, where the end stop sensor is located, then it moved a bit to the side, and then double backed to the sensor. When this file was implemented, it was tested and worked in the system, so this meant that after the tool traveled to the end stop sensor’s location, it changed to absolute values, which were moved to the middle of the 600 on 600 table. Because the limits of the M208 were changed back to the original values, this indicated that the system's limits were 300 from the middle. Which meant that inputting the command of G1 X0 Y0 F5000 provided the movement of the set area to the middle. And the z position, which was the bed of the system, moved to the starting height.



```
; homeall.g
; called to home all axes
;
G91                        ; Relative positioning mode
G1 Z5 F6000                ; Lift Z 5mm safely to clear the bed surface

; Detection of the end stop sensors
G1 S1 X-600 Y600 F3000  ; Move toward the back side of the system
G1 X5 Y-5 F6000            ; Backs away from the corner 5mm
G1 S1 X-600 Y600 F360   ; Move to the back side of the system again
slowly for a precise second click

; Establish the center of the bed as the 0 position
G90                        ; Absolute positioning mode
G1 X0 Y0 F5000             ; Move to the center of the system

G92 Z5.0                   ; Lock the current physical height as Z = 5.0mm
G1 Z0 F1000                ; Lower the Z to the absolute 0
G90                        ; Confirm absolute mode
```

Fig. 28. Altered Geometrical Code of the Homeall.g File

After the home button performed the correct actions, the extrusion of the linear actuator piston was tested. The system was connected to a compressor by Company X, and the test program was created in the .nc format. When these types of files were implemented through the SD card, they would become accessible through the PanelDue controller. The written program was depicted in Fig. 29.



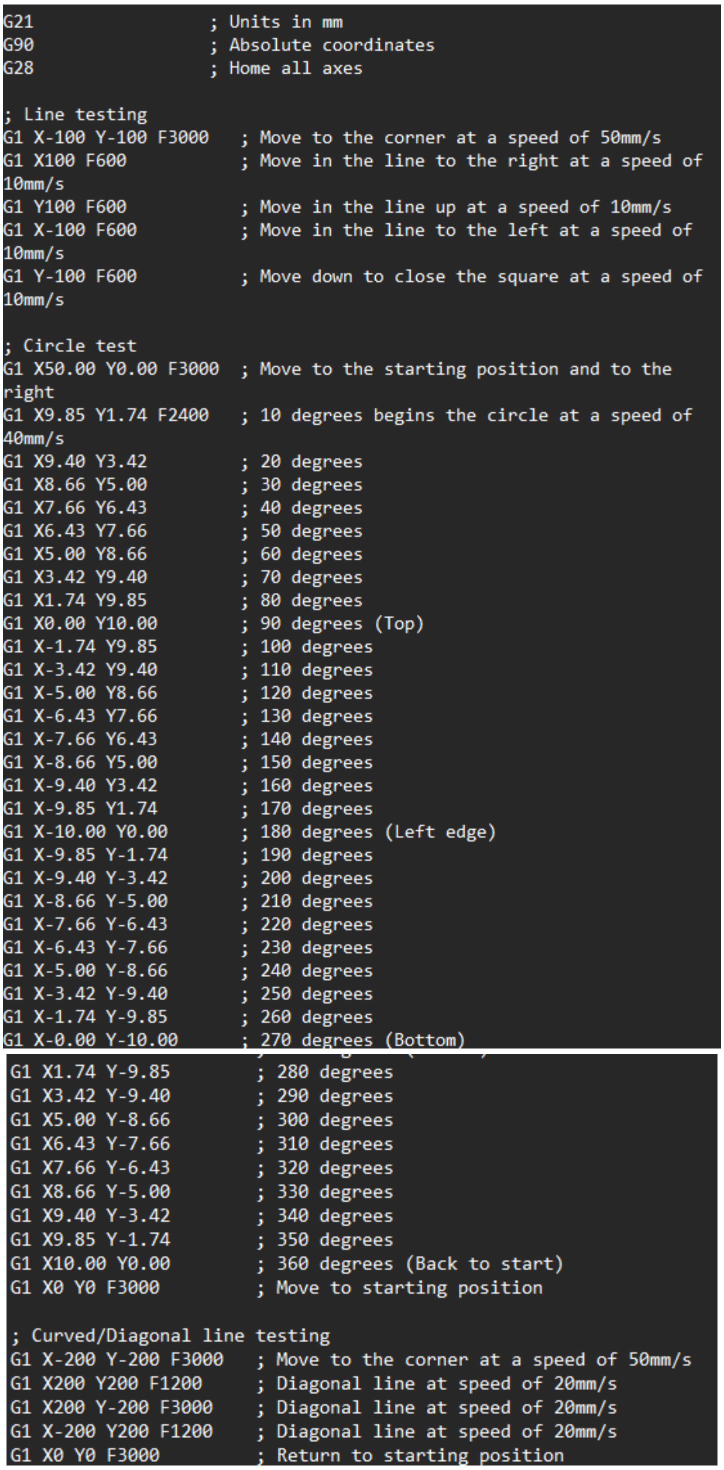
```
G90                 ; Absolute positioning
M106 P0 S255        ; Solenoid valve opens
G4 P500             ; Wait 500ms
M107 P0             ; Solenoid valve closes
G4 S3               ; Wait 3s
```

Fig. 29. The Testing Code for Pneumatic Linear Actuator

During this testing, the compressed air filter and regulator were set to 0.05MPa to produce a safe testing pressure. The Sika fast and push part was removed from the dispenser, and then the linear actuator movement was examined.

3.3. Test Protocols and Controlled Trials of the Dispensing System

After the system was calibrated and tested for dispensing, the code for controlled trials was created. The programs were run via the PanelDue controller and created in the .nc format. Firstly, the geometrical movement was tested with 3 tasks to create a square, a circle, and curved lines. The code was demonstrated in Fig. 30.



```
G21                   ; Units in mm
G90                   ; Absolute coordinates
G28                   ; Home all axes

; Line testing
G1 X-100 Y-100 F3000   ; Move to the corner at a speed of 50mm/s
G1 X100 F600           ; Move in the line to the right at a speed of
10mm/s
G1 Y100 F600           ; Move in the line up at a speed of 10mm/s
G1 X-100 F600          ; Move in the line to the left at a speed of
10mm/s
G1 Y-100 F600          ; Move down to close the square at a speed of
10mm/s

; Circle test
G1 X50.00 Y0.00 F3000  ; Move to the starting position and to the
right
G1 X9.85 Y1.74 F2400   ; 10 degrees begins the circle at a speed of
40mm/s
G1 X9.40 Y3.42         ; 20 degrees
G1 X8.66 Y5.00         ; 30 degrees
G1 X7.66 Y6.43         ; 40 degrees
G1 X6.43 Y7.66         ; 50 degrees
G1 X5.00 Y8.66         ; 60 degrees
G1 X3.42 Y9.40         ; 70 degrees
G1 X1.74 Y9.85         ; 80 degrees
G1 X0.00 Y10.00        ; 90 degrees (Top)
G1 X-1.74 Y9.85        ; 100 degrees
G1 X-3.42 Y9.40        ; 110 degrees
G1 X-5.00 Y8.66        ; 120 degrees
G1 X-6.43 Y7.66        ; 130 degrees
G1 X-7.66 Y6.43        ; 140 degrees
G1 X-8.66 Y5.00        ; 150 degrees
G1 X-9.40 Y3.42        ; 160 degrees
G1 X-9.85 Y1.74        ; 170 degrees
G1 X-10.00 Y0.00       ; 180 degrees (Left edge)
G1 X-9.85 Y-1.74       ; 190 degrees
G1 X-9.40 Y-3.42       ; 200 degrees
G1 X-8.66 Y-5.00       ; 210 degrees
G1 X-7.66 Y-6.43       ; 220 degrees
G1 X-6.43 Y-7.66       ; 230 degrees
G1 X-5.00 Y-8.66       ; 240 degrees
G1 X-3.42 Y-9.40       ; 250 degrees
G1 X-1.74 Y-9.85       ; 260 degrees
G1 X-0.00 Y-10.00      ; 270 degrees (Bottom)
G1 X1.74 Y-9.85        ; 280 degrees
G1 X3.42 Y-9.40        ; 290 degrees
G1 X5.00 Y-8.66        ; 300 degrees
G1 X6.43 Y-7.66        ; 310 degrees
G1 X7.66 Y-6.43        ; 320 degrees
G1 X8.66 Y-5.00        ; 330 degrees
G1 X9.40 Y-3.42        ; 340 degrees
G1 X9.85 Y-1.74        ; 350 degrees
G1 X10.00 Y0.00        ; 360 degrees (Back to start)
G1 X0 Y0 F3000         ; Move to starting position

; Curved/Diagonal line testing
G1 X-200 Y-200 F3000   ; Move to the corner at a speed of 50mm/s
G1 X200 Y200 F1200     ; Diagonal line at speed of 20mm/s
G1 X200 Y-200 F3000    ; Diagonal line at speed of 20mm/s
G1 X-200 Y200 F1200    ; Diagonal line at speed of 20mm/s
G1 X0 Y0 F3000         ; Return to starting position
```

Fig. 30. Geometrical Code for Testing the Movement of the System

This code tested if the program performed the movement tasks. After this step was completed and the system was determined to move accurately in lines, circles, and diagonals, the dispensing process testing began. For this, the toothpaste was used as a replacement for the adhesive material. The larger tank of the SikaFast was filled with it, which had a 3mm diameter nozzle. The toothpaste provided various advantages, which were needed for testing the operation under low pressure and consistency, like the adhesive materials of SikaFast. At first, a base program was created for the movement according to the components' bonding path, which served as a base program for the testing phase. The starting location was made according to the printed base component mounting part and it was moved to after the 0 position. The most suitable parameters had to be set and tested to produce the final program, which would be usable for manufacturing. The impacts of pressure, z-axis bed height, and speed were examined by altering these attributes. The first one observed was the z-axis height impact on the speed, which was set to a constant F1200, which was 20mm/s and the pressure was set to a constant 0.05MPa. The nozzle used was 3mm, so the bead width should be of that measurement. The starting position of the Z-axis was regulated according to the distance between the nozzle and the bonding component. The distance was increased from 5mm to 30mm, and each time the distance was increased by 5mm using the z-axis command to move. At the lowest distance, the dispensed line was accurate in bead width, and no complexities in the dispensing process were noticed. But when the distance was increased, a “tail” would form, and irregularities in the dispensed toothpaste were noticed, such as breaking, leaning, and expanding in certain areas. The cornering action was done at high inconsistency in these areas. This provided that the z-axis height should be lower, which provided a stable dispensed testing material. Pressure was changed from 0.05MPa to 0.08MPa; the compressed air pressure was increased by 0.01MPa. The material flow was affected at lower pressure, the adhesive was pushed more slowly, making the line thicker, and when it was increased a bit, the extrusion process increased. The noticed change provided that this parameter had to be regulated with the speed of the movement. These results indicate that the speed should not be altered and should be changed only in further testing. The program was altered, and the system had a constant 0.05MPa provided to it. The first test was performed at F450 speed and 15mm nozzle distance from the bonding component. The result was shown in Fig. 31.

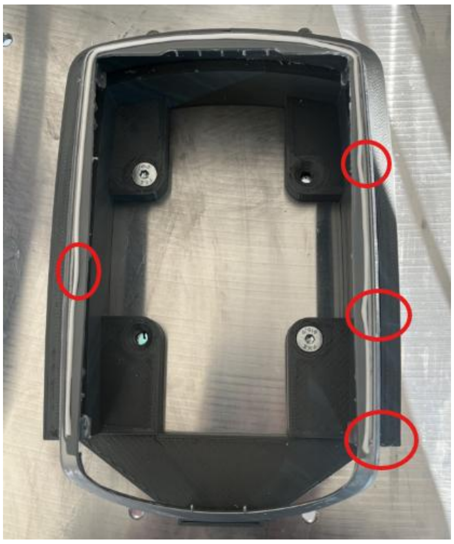


Fig. 31. Result of the First Dispensed Toothpaste on the Bonding Component Test with Red Circles Marking the Defected Areas

In the figure above, the areas where errors occurred were marked with red circles. Using the same parameters, the test was then performed 5 more times to provide more insight into what parameters affected this outcome. The distance between the nozzles was the factor that provided a defective result, because at this distance, in cases where the toothpaste did not hit the necessary path, the line would tangle mid-air. And the ending was caused by the linear actuator still applying pressure at the end of the would leave an uneven dispensed line. These parameters were fixed, the distance was lowered, and a timer was set at the end of the process, which indicated that the pressure should not be applied, and with the end residue, the path should be completed. The distance was lowered by 2 mm, and the solenoid valve stopped supplying for 4 mm. After 10 cycles were performed, the result was achieved and provided in Fig. 32.

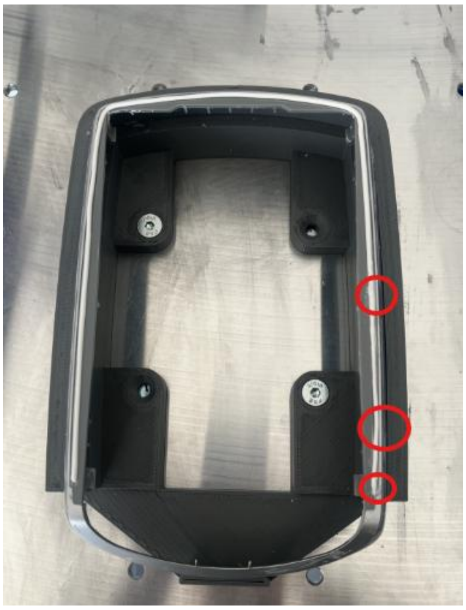
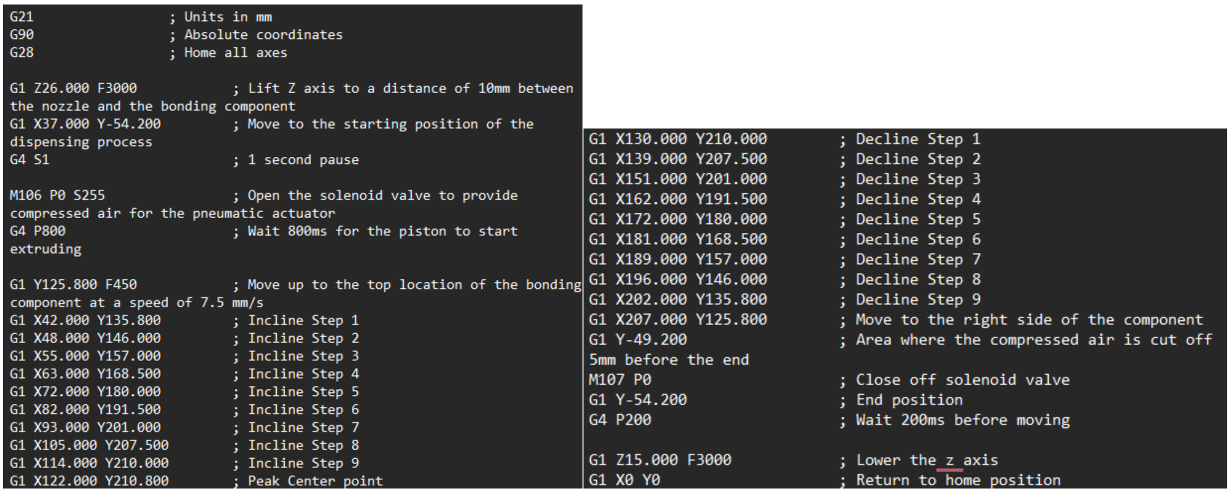


Fig. 32. Result of the Second Dispensed Toothpaste on the Bonding Component Test with Red Circles Marking the Defected Areas

In the figure above, the areas where errors occurred are depicted. As depicted in the figure above, some defects in the dispensed line can still be noticed, marked with the red circles. They occurred because there were still some defects in the height of the nozzle, and the time the system was turned off was still not enough; more length was provided to complete the end of the dispensed line. The final adjustments were made, the distance was changed to 10mm from the bonding component, and the distance where the solenoid shuts off was changed to 5mm. The final geometrical code was depicted in Fig. 33.



```
G21                 ; Units in mm
G90                 ; Absolute coordinates
G28                 ; Home all axes

G1 Z26.000 F3000            ; Lift Z axis to a distance of 10mm between
the nozzle and the bonding component
G1 X37.000 Y-54.200         ; Move to the starting position of the
dispensing process
G4 S1                       ; 1 second pause

M106 P0 S255                ; Open the solenoid valve to provide
compressed air for the pneumatic actuator
G4 P800                     ; Wait 800ms for the piston to start
extruding

G1 Y125.800 F450            ; Move up to the top location of the bonding
component at a speed of 7.5 mm/s
G1 X42.000 Y135.800         ; Incline Step 1
G1 X48.000 Y146.000         ; Incline Step 2
G1 X55.000 Y157.000         ; Incline Step 3
G1 X63.000 Y168.500         ; Incline Step 4
G1 X72.000 Y180.000         ; Incline Step 5
G1 X82.000 Y191.500         ; Incline Step 6
G1 X93.000 Y201.000         ; Incline Step 7
G1 X105.000 Y207.500        ; Incline Step 8
G1 X114.000 Y210.000        ; Incline Step 9
G1 X122.000 Y210.800        ; Peak Center point
```

```
G1 X130.000 Y210.000        ; Decline Step 1
G1 X139.000 Y207.500        ; Decline Step 2
G1 X151.000 Y201.000        ; Decline Step 3
G1 X162.000 Y191.500        ; Decline Step 4
G1 X172.000 Y180.000        ; Decline Step 5
G1 X181.000 Y168.500        ; Decline Step 6
G1 X189.000 Y157.000        ; Decline Step 7
G1 X196.000 Y146.000        ; Decline Step 8
G1 X202.000 Y135.800        ; Decline Step 9
G1 X207.000 Y125.800        ; Move to the right side of the component
G1 Y-49.200                 ; Area where the compressed air is cut off
5mm before the end
M107 P0                     ; Close off solenoid valve
G1 Y-54.200                 ; End position
G4 P200                     ; Wait 200ms before moving

G1 Z15.000 F3000            ; Lower the z axis
G1 X0 Y0                    ; Return to home position
```

Fig. 33. Final Program of the Dispensing Process

The final program was run for 10 cycles, a perfect result, which was depicted in Fig. 32, was achieved. Although this was successfully achieved, it was done in perfect conditions, when the storage area was full, at a constant pressure of 0.05MPa, and the system was run after some time. More cycles using this program were run through 20 cycles, but only in the first one was the perfect dispensing process noticed. Some deviations were also observed; the system would show signs of precision inaccuracies, where the bead width would shrink or thicken. Also, the path would deviate by around 1-3mm after performing around 10-12 cycles.

Fig. 34. Result of the Dispensing, with a Successfully Extruded Line

3.4. Chapter Summary

The required components were put into a BOM, which was then sent to Company X, describing the amount and where these components will be used. To perform successful modifications, the 3D printer platform was measured and evaluated, which provided insight into what components should be left and which should be removed. The necessity of custom-made and printed components was noticed, which meant that two components were designed. One was the mounting component, which was made according to the received SikaFast pneumatic linear actuator measurements and the mounting area. Then the push part was designed to act as an intermediate between the SikaFast and pneumatic linear actuator. Both components were tested using PrusaSlicer to make sure they can be printed. Then the assembly of the system was performed, the dispenser was assembled using the printed components and the linear actuator, SikaFast, and was mounted to the linear motion drivers. Then the pneumatic system was assembled using the components provided in the BOM. After everything was done, the movement was tested to make sure that nothing was loose. The calibration step was then performed using the controller accuracy, and the working of the pneumatic solenoid valve was tested. Then the system 0 position was defined using the home button, and the movement of the pneumatic linear actuator was tested. After that, the geometrical movement code was created to perform a movement test. Finally, the dispensing testing was performed, providing information on what factors affected the process. Testing on the bonding component was performed, and perfectly dispensed material during perfect conditions was achieved.

4. Evaluation of the Dispensing System

The proposed dispensing system can be compared to other already existing ones, but firstly, the economic aspect should be evaluated. The cost of the added components was entered into Table 8. only the newly added components from the dispenser side and the pneumatic system were calculated. The printed components were weighed to determine how much material was used.

Table 8. Economic Evaluation of the Added Components

Component	**Price**
Pneumatic linear actuator SMC CD55B40-150	116 euros [88]
Around 500 grams of PLA material for the printed mounting component	11.5 euros [102]
Pneumatic solenoid valve SVC V6110-M5-D24	58 euros [93]
Compressed air filter SMC AW20-F02E-B	80 euros [97]
Compressed air regulator SMC AR20-F02	55 euros [99]
Around 200 grams of PLA material for the printed push part component	4.6 euros [102]
Around 400 grams of PLA material for the printed mounting of the	9.2 euros [102]
Silencer SMC AN101-G01	2.50 euros [92]
Fitting SMC KQ2H06-G01A	2.95 euros [91]
Pneumatic tubbing 6mm – 2m	4 euros [103]
Fitting KQ2H06-M5A	2.92 euros [94]
Silencer SMC AN05-M5	3.30 euros [95]
Pneumatic tubbing 10mm – 6m	15 euros [103]
Fitting SMC KQ2H10-M5A	3 euros [96]
Y-fitting SMC KQ2U10-02AS	8.62 euros [100]
Connection SMC KK4P-02F	2.50 euros [98]
Fitting KQ2H10-02AS – 2x	5 euros [101]
Mounting bracket SMC AW23P-270AS	3.70 euros [104]
Mounting bracket SMC AR23P-270AS	3.83 euros [104]
Total	391.62 euros

The total price for components needed for modification was 391.62 euros, which is exponentially cheaper than the automated systems, which were discussed in Table 1. Into this final sum, the cost of the 3D printer was not included, because it was provided by Company X. In areas where the dispensing system is necessary, this is a perfect solution, especially if the manufacturer also has 3D printer devices, which are not being used. Scalability is possible through choosing different components, which could be designed and printed to fit smaller or larger 3D printer platforms. Also, the manual labour and designing time are not measured in this table. The system was constructed using safety precautions, which were used at low pressure to avoid any damage. The 3D printer platform was measured intensely to avoid any damage that could occur during the process. Manual movement was performed before any automated operation. The assembled and tested system provides customization capabilities needed in the manufacturing industry. But, comparing this to other widely manufactured systems, it would still require more testing and adjustments to perform actions accurately during each cycle, not only during perfect conditions.

4.1. Chapter Summary

The economic evaluation was performed to understand the price of the assembled system. Only the new components were discussed. This information provides the ability to compare with the already existing automated dispensing systems. The total amount was 391.62 euros, which, when compared to other manufactured automated dispensing systems, can differ a lot. Certain criteria were not calculated in the table, which would increase the price by some amount. The safety precautions were taken into consideration when designing and developing the system. This developed system was compared to the widely manufactured solutions, which provided an insight into further modifications.

Conclusions

1. The analysis conducted identified the advantages and disadvantages of the current automated dispensing solutions. Each method was analysed, which provided an insight into how they operate and what components are necessary to achieve them. The importance of viscosity was determined, and the limitations of each solution were determined, which shows what adhesives can be used. Precision was analysed, showing how certain solutions, such as syringe-type dispensing, can be used to achieve the required deposited material width. Common control approaches and failure models provided an insight into what connections must be made to create a synchronized working environment and which mistakes should be avoided.
2. The research identified the necessary system requirements, the bead width of 3mm, accuracy, and precision close to 0. Using tested methods, the solution of volumetric dispensing with a pneumatic actuator was selected as the most suitable solution. The existing 3D printer components were identified, which provided what should be removed and what should be untouched. Analysis of the system provided a requirement, which was that the dispenser had to be designed to fit into the existing platform. Pneumatic components that were used in the dispensing system were selected according to the research done on this subject.
3. The modifications to the system were performed successfully. The components were designed to fit into the working area of the existing platform; the final height of the assembled dispenser was around 466 mm. The movement was tested at different variables through the controller to ensure the assembled component was sturdy. The pneumatic system was also integrated successfully, and tubing issues were avoided. The components were assembled according to the pneumatic scheme provided. The accuracy issue was solved through calibration by providing the permanent 0 position to the platform, which helped operate the modified system.
4. Controlled trials were performed to ensure that the system's movements were accurate. Movement in square, circle, and diagonal lines was performed, which provided insight into whether the system moves according to the provided commands. The system was connected to the compressed air source, and almost every test was performed at a constant 0.05MPa pressure to avoid any damage to the system and to the person operating it. Multiple testing was performed mostly by changing the z-axis. The best solution for this parameter was indicated as 10mm between the nozzle and the bonding component. The speed at which the system was operated successfully was 7.5 mm/s, which was determined as the most optimal speed to achieve the desired result. A successful dispensing process was achieved at perfect conditions of the system, where the adhesive storage area was filled with toothpaste and the system was just started.
5. The developed system performed the provided commands accurately. Although after running multiple cycles with the determined program, a deviation in the dispensed line was noticed. After around 10-12 cycles, while testing the system consistently previously, an error of 1mm to 3mm, where the system dispensed the line not accurately, this may be caused by the emptying capacity of the storage area, the speed, or outside factors such as an increase in temperature. The economic aspect of the system was analysed. The total cost of modifications was 391.62 euros, which was cheaper than the automated systems provided by various manufacturers.

Further recommendations would be to perform more tests to find even more optimal parameters that would provide constant, accurate dispensing. Other designs of the dispenser should be developed to provide the necessary strength to operate at higher pressures. Additional sensors should be researched to provide more information about how the system operates and which aspects should be modified to increase performance and accuracy even more. Additionally, throttle control should be added to the linear pneumatic actuator to provide more control over the dispensing process. Testing with the adhesive material should be performed to provide more insight into what aspects could be modified even more.

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Appendices

Appendix 1. Commands of the PanelDue controller

Code	**Definition**
M106	For the dedicated fan ports, turn on the command
P0	Identifies that the Fan port 0 should be used
S255	Indicates that the power should be 100%
M107	For the dedicated fan ports, turn off the command
M208	Defines the minimum and maximum of the axes.
G21	System moves in the mm units
G90	Refers to the current position as 0,0
G28	Home location
G1	Movement
F	Speed
I	Radius
J	Direction
M119	For running diagnostics of the endpoint sensors
S	End point sensor detection
M574	Determines how the end stop operates