KU LEUVEN

FACULTEIT INDUSTRIËLE
INGENIEURSWETENSCHAPPEN

CAMPUS BRUGGE

Automation of an adhesive application by using a robot

Jorrit WILLAERT

Promotoren: prof. dr. ing. S. Debruyne
dr. ir. F. Debrouwere

Begeleider: ing. S. Fevery

Masterproef ingediend tot het behalen van de graad van master of Science in de industriële wetenschappen: Elektromechanica

Academiejaar 2019 - 2020

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Abstract (Nederlands)

De industrie evolueert naar een industrie 4.0 met een nadruk op intelligente machines, waarbij *artificial intelligence* de efficiëntie van productielijnen wenst te verbeteren. Deze studie tracht met behulp van machinevisie, een deelgebied van *artificial intelligence*, de uniformiteit en de uithardingstoestand van een lijmverbinding te bepalen. De uithardingstoestand van de lijm kan hierbij afgeleid worden uit de kleur van de lijm, vermits deze wijzigt naarmate de lijm uithardt. Echter, om de resultaten van verschillende proefstukken objectief met elkaar te kunnen vergelijken, dient het lijmproces geautomatiseerd te verlopen. Hiervoor wordt gebruikt gemaakt van een lijmunit in combinatie met een robot, waarbij representatieve proefstukken bestaande uit een lijmverbinding tussen aluminium en plexiglazen platen geproduceerd worden.

De communicatie tussen de robot en de lijmunit dient opgezet te worden. Hierdoor worden zowel de noodstoppen van de beide machines gesynchroniseerd, waarnaast tevens de mogelijkheid aan de robot toegereikt wordt om een extrusieverzoek te sturen naar de lijmunit. Daarnaast is er in dit onderzoek gekozen om de plexiglazen platen met behulp van de robot naar de lijmdispenser te brengen, welke een bijkomend voordeel met zich meebrengt dat de verlijmde proefstukken tevens gestockeerd kunnen worden.

Voor het opnemen van de plexiglazen platen wordt gebruik gemaakt van een vacuümgrijper, aangezien deze de mogelijkheid bezit om de platen op één zijde vast te nemen, dit in tegenstelling tot conventionele grijpers waarbij gebruik gemaakt wordt van minstens twee zijden. Hierdoor blijft de keerzijde van de plexiglazen plaat volledig vrij, waardoor de flexibiliteit van de toepassing toeneemt.

Gebruik makend van deze componenten en connecties kon de praktische uitwerking voor het produceren van representatieve samples vervolledigd worden. Het was echter nog niet mogelijk om reeds proefstukken te produceren aangezien er slechts één persluchtaansluiting voorhanden was, terwijl zowel de lijmunit als de robot gelijktijdig van perslucht voorzien moet worden. Daarnaast werd tevens vastgesteld dat de mixeenheid bij de lijmdispenser tijdens het verstrekken van lijm grote afwijkingen ondervond. Dit kon echter vrij snel opgelost worden met een gefixeerde ring rond de mixeenheid, doch werd dit uitgesteld aangezien de productie nog niet kon aanvatten vanwege de enkele persluchtaansluiting.

Daarnaast dient een camera gemonteerd te worden die oordeelt over de kwaliteit van de verlijming van de proefstukken. Aangezien de resolutie van de camera te laag is om een kwaliteitscontrole uit te voeren indien deze gemonteerd is boven de robot zijn werkzone, is ervoor gekozen om de camera met behulp van een draaiende constructie te monteren in de robot zijn werkzone. Met deze opstelling is het bijgevolg mogelijk om de kwaliteit van de ene batch werkstukken te controleren terwijl de robot een andere batch produceert.

Voor het effectieve programmeerwerk werd uiteindelijk besloten om de Fanuc TeachPendant te gebruiken. Deze programmeeromgeving heeft echter als nadeel dat deze geen geïntegreerde mogelijkheid biedt om een Python script in te laden, waardoor een externe Raspberry Pi gebruikt wordt om visiemogelijkheden te verkrijgen.

De COVID-19 uitbraak zorgde er echter voor dat bepaalde componenten zoals de roterende constructie niet meer vervaardigd konden worden. Hierdoor werd besloten om de kwaliteitscontrole conceptueel verder uit te werken, hetgeen inhoudt dat de setup gemodelleerd wordt in een CAD omgeving en dat bepaalde connecties beschreven worden. Helaas was de mixeenheid nog niet gefixeerd op het moment dat de restrictie tot de KU Leuven campus te Brugge ingevoerd werd, waardoor er amper proefstukken beschikbaar waren voor de verdere implementatie van het visie-algoritme. Daarnaast bleek de kleurverandering doorheen de uithardingsperiode van de lijm amper kwantificeerbaar uit de analyse van de beschikbare proefstukken.

Er kan geconcludeerd worden dat deze opstelling alle capaciteiten bezit om representatieve proefstukken te produceren na de fixatie van de mixeenheid. De kwaliteitscontrole daarentegen kan bij deze lijm nog niet ingezet worden, aangezien de kleurverandering doorheen de uithardingsperiode van de lijm niet eenduidig vastgelegd kon worden.

Trefwoorden: Industrie 4.0, machinevisie, lijmunit, robot, vacuümgrijper

Abstract

Industry is evolving towards industry 4.0 with an emphasis on intelligent machines, where artificial intelligence aims to improve the efficiency of production lines. This study attempts to determine the uniformity and the curing state of an adhesive joint by using machine vision, a sub-area of artificial intelligence. The curing state of the adhesive can be deduced from the colour of the adhesive, since this colour changes over the curing time. In order to objectively compare the results of different adhesive joints, the gluing process must be automated. Therefore, an adhesive dispensing machine is used in combination with a robot to produce representative samples, consisting of an adhesive bonding between aluminium and plexiglass plates.

The communication between the robot and the adhesive dispensing machine must be established. As a result, both the emergency buttons of the two machines are synchronised, while the robot also has the ability to send an extrusion request to the adhesive dispensing machine. Moreover, in this research it was decided to bring the plexiglass plates to the adhesive dispensing nozzle with the robot, which has an additional advantage that the glued samples can be stored as well.

A vacuum gripper is used to pick up the plexiglass plates, since it has the ability to hold the plates on one side, unlike conventional grippers that require at least two sides. This ability leaves the opposite side of the plexiglass plate completely free, which increases the flexibility of the application.

Using these components and connections, the practical elaboration of the production cycle could be completed. However, it was not yet possible to produce samples since there was only one compressed air supply available, while both the adhesive dispensing machine and the robot had to be supplied with compressed air. In addition, it was also determined that the mixing unit at the adhesive dispensing nozzle experienced large deviations during dispensing. This could be solved fairly quickly with a fixed ring around the tip of the mixing unit, but was postponed as production could not start yet due to the single compressed air supply.

In addition, a camera must be mounted to evaluate the quality of the bonded samples. Since the resolution of the camera is too low to perform a quality control if it is mounted above the robot's working zone, it was decided to mount the camera in the robot's working zone by using a rotating construction. Therefore, it was possible with this setup to evaluate the quality of one batch of samples while the robot produces the next batch.

The Fanuc TeachPendant has been used for the programming work. Nevertheless, this programming environment has the disadvantage that it does not offer an integrated possibility to load a Python script. An external Raspberry Pi is therefore required to obtain vision capabilities.

However, the COVID-19 outbreak meant that certain components such as the rotating construction could no longer be manufactured. As a result, it was decided to elaborate the desired quality control conceptually, which means that the setup is modelled in a CAD environment and that certain connections are described. Unfortunately, the mixing unit was not yet fixed when the access to the KU Leuven campus in Bruges was suddenly restricted, so hardly any samples were available for the further implementation of the vision algorithm. In addition, the colour change during the curing period of the adhesive is almost undetectable from the analysis of the available samples.

It can be concluded that this setup has the capability to produce representative samples after the fixation of the mixing unit. Contrarily, the quality control cannot yet be used with this adhesive, since the colour change over the curing period of the adhesive has not been detected unambiguously.

Keywords: Industry 4.0, machine vision, adhesive dispensing machine, robot, vacuum gripper

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This research work is the final step to obtain my master's degree in electromechanical engineering at the Catholic University of Leuven. The past four years have been an incredible instructive time in which many different topics were taught. Throughout those years, it became clear for myself that I like the mechatronic subjects the most, hence my thesis subject was an easy choice when I got the opportunity to work with a robot.

There are several people that I would like to thank for supporting me throughout the past nine months. First of all, I would like to express my gratitude to my supervisors ing. S. Fevery, dr. ir. F. Debrouwere and prof. dr. ir. S. Debruyne for the support and the constructive feedback they gave me during the course of this research. Their extensive knowledge helped me to develop my skills in topics ranging from practical aspects to programming and even to the expansion of my English knowledge. I would further like to express a special thanks to ing. S. Fevery for the several hours he directly helped me with practical problems during my internship as well as the answering of many mails during the whole course of this research. Additionally, I would like to thank ing. M. De Ryck for his expertise involving the Fanuc robot.

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Jorrit Willaert
Leffinge, May 27, 2020

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List of Symbols

Symbol	Description	Unit
A	Surface	m^2
d	Diameter	m
F	Force	N
g	Gravitational acceleration	m/s^2
m	Mass	kg
p	Pressure	Pa

List of Abbreviations

ACK	Acknowledgement
CAD	Computer-aided design
Cobot	Collaborative robot
COVID-19	Coronavirus disease 2019
DCS	Dual Check Safety
e.g.	Exempli gratia (For example)
et al.	Et alia (And others)
etc.	Et cetera
i.e.	Id est (That is)
I/O	Input/output
IoT	Internet of Things
KU Leuven	Katholieke Universiteit Leuven (Catholic University of Leuven)
LED	Light-emitting diode
M-Group	Mechatronics Group
MS polyethers	Modified Silane polyethers
NPN transistor	Negative-Positive-Negative transistor
PNP transistor	Positive-Negative-Positive transistor
Propolis	Processing of Polymers and Innovative Material Systems
RGB	Red Green Blue
ROS	Robot Operating System
SMP	Silyl Modified Polymers
TCP/IP	Transmission Control Protocol/Internet Protocol
UV	Ultraviolet
VEE	Vacuum End Effectors

1 Introduction

Industry is evolving towards Industry 4.0, which consist mainly of the Internet of Things (IoT), intelligent machines, Big Data and smart manufacturing. Machines increasingly obtain more sensors, which by sharing their measurements with each other, lays the foundation for the IoT. The machines used in industrial assembly lines are frequently robots, which seek to improve the lead times, the reliability and many others. Whereas earlier robots worked in separate work cells, contemporary robots are made to work in collaboration with humans, hence called cobots. Such a setup combines the experience and knowledge of human operators with the reliability and forcefulness of cobots, therefore reducing heavy physical labour.

Another major trend in manufacturing industries is the awareness of quality control along with the importance of reducing wastes to maximize the value for the customer, embraced in the term 'Lean six sigma'. The eight types of wastes in lean manufacturing are enumerated by G. Atti [13]:

1. Defects in products and services[1]
2. Overproduction
3. Transport
4. Waiting
5. Unnecessary inventory
6. Unnecessary motion
7. Overprocessing
8. Inappropriate use of human resources skills

This study will partly focus on addressing some wastes, mainly the reduction of defects and minimizing waiting times. Those wastes can be addressed by monitoring the production to know exactly

[1] This waste is strongly connected with six sigma.

at what time a particular sample may move in the line. Another major part of this study concerns the connections between the different subsystems of the setup. Those connections come in a variety of formats, ranging from linking the emergency buttons to exchanging high-level data, such as vision capabilities.

Section 1.1 revolves around the composing of the research questions, presuming the desired outcome. Consequently, Section 1.2 proposes an approach to divide the research down in subproblems which are more amenable. Furthermore, an overview of this research is provided in Section 1.3.

1.1 Problem statement

The research group Propolis (Processing of Polymers and Innovative Material Systems) of the KU Leuven campus Bruges has done a lot of research on polymer structures for many years [14]. Consequently, some specific extrusion and injection moulding machines are available on the campus, as well as a certain two-component adhesive dispensing machine. This adhesive machine had no specific usage yet, although there were ideas in the M-Group of KU Leuven to research the strengths and weaknesses of a bound consisting of a two-component adhesive. However, it was not desirable to produce such samples by hand, since it would be hard to compare them objectively.

This study will therefore use a robot in combination with the adhesive dispensing machine, to produce representative samples[2] on which a variety of experiments can be conducted. Nevertheless even an automated application may experience random errors either caused by human mistakes or a random fluctuation in a component. An additional investigation has therefore been performed to obtain a quality control on the samples based on vision capabilities that can be achieved with the usage of a camera.

The two research questions are summarized as follows:

1. Could representative samples, consisting of aluminium and plexiglass plates joined by an adhesive bond, be produced with an automated gluing process assisted by a robot?

2. Could the uniformity and the curing condition of an adhesive bond be determined with a camera, by using an adhesive which colour is curing-dependent?

1.2 Approach

The whole setup can be divided in a few subcomponents whose individual working processes are investigated in the first part of this study. The second research question is in this part of the study less relevant since it can only be investigated once the main setup with the robot and the adhesive dispensing machine works as desired. The first objective of this research is therefore to link the adhesive dispensing machine with the robot to achieve communication between them. Once a communication has been established, the programming of the robot may start to investigate the first research question. However, there was only one compressed air supply and it was mandatory to provide both the robot and the adhesive application with compressed air to commence the production. Therefore, there had been waited to produce samples while in the meantime the investigation of the second research question began. Unfortunately, the COVID-19 outbreak forced the plans to

[2]The production of comparable, uniformly cured samples is termed producing representative samples.

change since the access to the KU Leuven campus in Bruges was suddenly restricted. The decision has therefore been made to elaborate the second research question conceptually and to draw conclusions on both research questions from experiences rather than from objective experiments conducted on the samples.

1.3 Overview

This thesis is organised in the following order:

- 'Chapter 1: Introduction' presents the problem statements and formulates appropriate research questions.
- 'Chapter 2: Literature survey' aims to gain knowledge of the subjects examined in this research.
- 'Chapter 3: System setup' describes the outline of the system along with its subcomponents and the established connections between them.
- 'Chapter 4: Conceptual work — Vision capabilities' describes a conceptual explanation of the components that are desired to obtain vision capabilities.
- 'Chapter 5: Program' provides a qualitative analysis of the robot program along with the different subroutines in the vision program.
- 'Chapter 6: Discussion and conclusions' summarizes the findings and the limitations of this research with in addition some recommendations that may be useful for future work.

2
Literature survey

2.1 Introduction

This chapter surveys the available literature on the subjects examined in this research.

Section 2.2 investigates the main factors influencing adhesives. Besides, some specific adhesives and typical bond configurations were elaborated. Moreover, the automated adhesive bonding application is based on a pick-and-place system, causing the need of grippers. Hence, the possible approaches are discussed in Section 2.3. Subsequently, Section 2.4 sheds light on the variety of existing automated adhesive bonding applications with a secondary approach to robots with more cognitive capabilities.

2.2 Adhesive bonding

According to S. Wu [15], adhesion refers to the state in which two dissimilar bodies are held together by intimate interfacial contact such that the mechanical force and hence work can be transferred across the interface. Although this book was published in 1989, the definition is still used in more recent work [16].

The bonded joint (Figure 2.1) refers to the union of two adjacent adherends[1] through an adhesive. Therefore, the joint designates the assembly formed by the adherends, the adhesive, by any additional products that might be used (e.g. a primer) and all associated interphases [17].

Bonded joints will be denoted as samples, since they are the objects of this study. Moreover, a primer is a substance which is often applied on the adherend to improve adhesion or protect the surfaces until the adhesive or sealant application. The region between the adhesive and the adherend is referred as the interphase. The interphase has chemical and physical characteristics different from those of the bulk adhesive or adherend. Hence, the nature of the interphase is a critical factor in the determination of the mechanical properties of the adhesive bond [1]. The

[1] A substrate is synonymous with an adherend.

interface, different from the interphase, is the plane of contact which is formed by the boundary between adherend and adhesive. By definition an interface has area but no volume, in contrast to the interphase which has a volume as well [1][18].

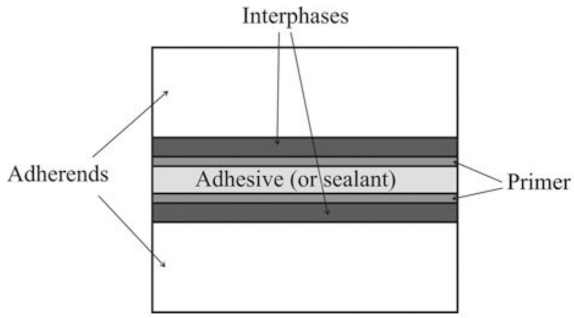


Figure 2.1: Adhesive joint [1]

2.2.1 Characteristics

One of the major advantages of adhesives over other bonding techniques is the more uniform stress distribution. This implies a higher stiffness, a better load transmission, the reduction of weight and a lower cost. Besides stress transmission, adhesive joints provide good damping properties and a high fatigue stress due to the polymeric nature of the adhesive. The very smooth surface finish is another benefit since adhesives avoid the use of holes for rivets or bolts. On the other hand, adhesives do have some disadvantages like a limited resistance to extreme temperatures [2] and humidity conditions. In addition, the curing process requires a heating device for many adhesives, which is a big economical disadvantage. Other disadvantages are a more difficult quality control and a necessary surface preparation [1].

2.2.2 Requirements

The basic requirements for a good adhesive bond are [19]:

- Proper choice of adhesive
- Good joint design
- Cleanliness of surfaces
- Wetting of adherends
- Proper adhesive bonding process[3]

This research focuses on the correct selection of an adhesive, a correct design and the required surface treatments.

[2] Upper service temperatures are limited to approximately 177 °C in most cases, up to 371 °C for special adhesives with limited use [16].

[3] Maintaining a good solidification and cure process.

2.2.3 Choice of adhesive

There are two principal types of adhesive bonding: structural and non-structural. Structural adhesive bonding is bonding for applications in which the adherends may experience large stresses up to their yield point. Therefore, a structural bond has been defined as having a shear strength greater than 7 MPa, with in addition a significant resistance to aging. Non-structural adhesives are not required to support substantial loads, but merely hold lightweight materials in place [16]. This research focuses on structural adhesive bonding since a variety of destructive experiments will be conducted on the samples.

There are several methodologies for choosing an adhesive for a specific application. One of them is to first consider the function of the adhesive (structural, non-structural) and to then consider the durability that it must present in the service conditions to which the bonded connection will be exposed. By using this procedure, it is possible to reduce the vast amount of commercial adhesive products available to just a few. To further reduce the number of possible adhesives for the application in question, other factors must be considered such as the type of substrate, the magnitude and duration of the applied loads, thickness of the bond line and environmental conditions [17].

This study sheds light on some specific structural adhesives. In particular epoxies, cyanoacrylates, hotmelts, polyurethanes and silyl modified polymers. In addition, the working principle and general design of a two-component adhesive is explained.

Investigated adhesives

Epoxies Epoxy adhesives are built of groups containing two carbon atoms and one oxygen atom in an annular structure. Because of the wide versatility and basic adhesive qualities, epoxies are excellent structural adhesives that can be engineered to widely different specifications. The reason is an achievement of very high cohesion and adhesion elastic strength, due to which they face no competition from any other polymeric materials. Nevertheless, epoxies have relatively low peel strength [20][21].

Cyanoacrylates Cyanoacrylates cure rapidly at room temperature and exhibit excellent tensile strength and good shelf life. They also have long pot life[4] and good adhesion to metal. Limitations include high cost, poor peel strength, brittleness and capability to fill only small gaps. Furthermore, substrates need to be mated as quickly as possible to reduce the possibility of contamination [23].

Hotmelts Hot-melt adhesives are thermoplastic bonding materials applied as melts that achieve a solid state and resultant strength on cooling. These thermoplastic 100 % solid materials melt in the temperature range from 65 °C to 180 °C. When hot-melt adhesives are used, factors such as the softening point, melt viscosity, melt index, crystallinity, tack, heat capacity and heat stability must be taken into account, in addition to the usual physical and strength properties. Unlike other adhesives, the set-up process is reversible and at about 77 °C, most hot melts begin to lose strength [21].

[4] Pot life is the time available between mixing an adhesive and curing [22].

Polyurethanes Under the name of polyurethanes (PU), a practically unlimited number of structures can be considered [24]. Most of the time, PU is generally formed by a chemical reaction between an isocyanate and a polyol, forming repeating urethane groups in presence of a chain extender, catalyst or other additive. Isocyanates are essential components required for PU synthesis. These isocyanates contain at least a pair of two –NCO groups per molecule [25]. The other main component, polyol, is formed by a base-catalyzed addition of propylene or ethylene which oxides onto a hydroxyl or amine containing initiator [24].

The overall properties of polyurethanes depend on the intrinsic properties of each of the phases, which in turn depend on the details of molecular packing of the constituents within the phases, including the density of the hydrogen bonds. There are no hard and fast rules for obtaining the optimum polyurethane elastomer end product. Success depends on good formulation and well chosen, appropriate processing parameters [24]. This makes polyurethane a versatile adhesive which can be customized to suit the requirements of a particular industry [26].

Either way, polyurethane adhesives have the property that even before the adhesive dries and seals completely, the initial bond is strong enough to prevent clamps and other types of securing instruments from being needed. Furthermore, polyurethanes tend to be very flexible, durable and they provide good impact resistance [26].

One major drawback of uncured polyurethane-based sealants and adhesives is the presence of unreacted isocyanate groups which are very reactive and harmful to humans in various forms and thus undesirable. In particular, isocyanate groups react with H_2O, forming CO_2 which induces the formation of voids within the material, thereby promoting cohesion failure [27].

Silyl modified polymers Modified silane (MS) polyethers or silyl modified polymers (SMP) maintain strong adhesion for a wide range of substrates (e.g. metal, ceramic, plastics, glass, etc.), have good temperature and UV resistance along with an excellent durability with limited surface treatment. In particular, SMPs are widely used to bond directly to glass with minimal surface preparation and are suitable for large surface areas within adequate working times while providing actual insulation. Another particular advantage of SMPs is that they are environmentally and industrially attractive water-based and solvent-free adhesives for which shrinkage, typically encountered with solvent-based adhesives, hardly occurs upon curing. Finally, SMPs represents an alternative to polyurethanes used in the adhesives, sealants and paint industries. This because the SMPs are far less reactive, hence have less voids [27].

Two-component adhesives

Two-component adhesives have to be mixed before their application. The correct mixing of the adhesive is a precondition to achieve a good homogeneity of the mixture and to obtain the best mechanical performance of the bond. There are many types of mixing methods, ranging from vacuum mixers to kneaders and centrifuges [28].

The transferring of the adhesives out of drums and pails is commonly done by using a follower plate combined with a pulping or gear pump. The product is further transferred through pipes and possibly a dozer to a nozzle which applies the adhesive to the area to bond. However, gear pumps have certain disadvantages, such as bringing shear stress into the adhesive and raising the temperature, causing an increased viscosity [28].

General design of a metering and mixing machine The machine-processing of adhesives involves a number of different tasks [2]:

1. Maintaining a stock of adhesive
2. Removal of the adhesive from a storage container
3. Transporting the adhesive
4. Dosing the adhesive
5. Mixing the adhesive
6. Applying the adhesive

Figure 2.2 shows the schematic representation of a two-component dosing and mixing system.

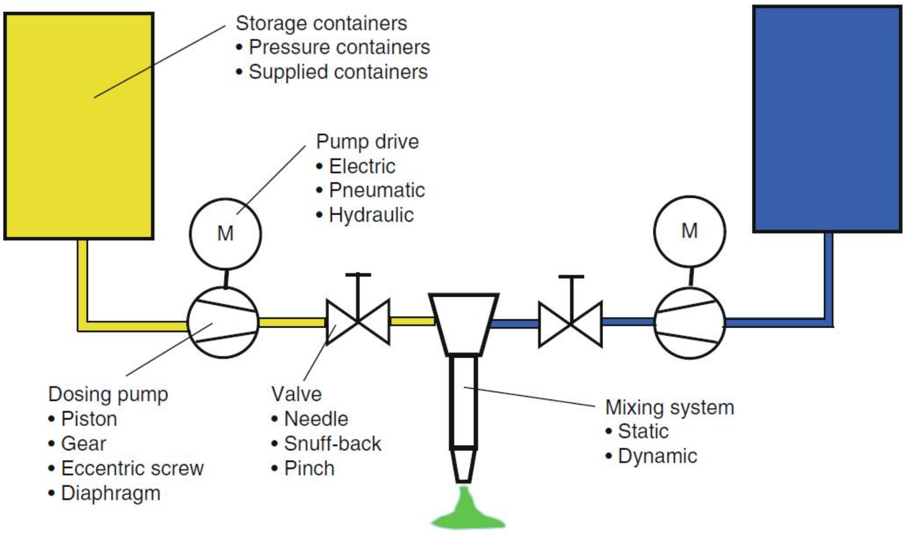


Figure 2.2: Schematic representation of a two-component dosing and mixing system [2]

2.2.4 Good joint design

One of the main reasons for the increasing use of adhesive bonding is the fact that the stress distribution is more uniform than with other conventional methods of joining, which enables to reduce weight. However, even in adhesive joints the stress distribution is not perfectly uniform, leaving room for improvements because failure always occurs at the stress concentrations. The major enemies of adhesive joints are peel and cleavage stresses, which must be reduced if strong joints have to be designed [5].

To obtain the maximum effectiveness of an adhesive bond, the bonded area should be as large as possible. Subsequently, a maximum percentage of this bonded area should contribute to the strength of the joint. In addition, the adhesive should be stressed in the direction of its maximum strength [3].

Types of stresses

Five types of stresses may occur at adhesive joints: compression, tension, sheer, peel and cleavage (Figure 2.3). A joint loaded with compression is less likely to fail than when loaded in any other manner. Shear stresses imposes an even stress across the whole bonding area, utilizing a joint that is most resistant to joint failure, just like with tension. The two worst adhesive stresses are peel and cleavage stresses, which are quite similar to each other, but peel stress is applied to a joint where one or both of the adherends is flexible. The stresses for peel and cleavage are not evenly distributed, but concentrated on one side of the joint, resulting in peak stresses. These cause the bond to fail easily [3].

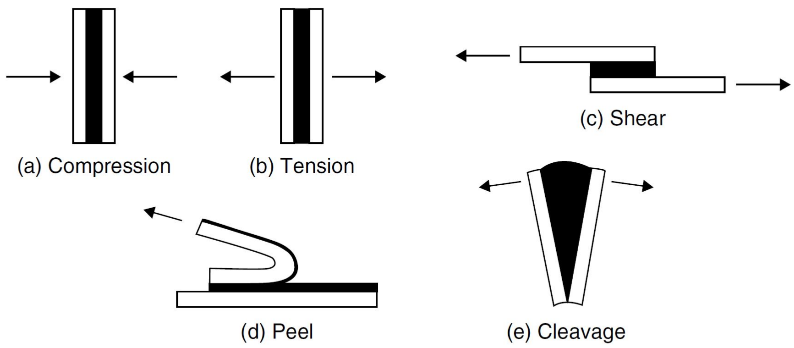


Figure 2.3: Types of stresses in adhesive joints [3]

Bonded joint configurations

A large number of adhesively bonded joint configurations use an overlap in their construction. These are generally referred to as simple lap joint geometries. Most of the time, when designing a bonded joint, the ideal approach is to ensure that the bonded joint is stronger than the adherends. However, it can be shown that the load carrying capacity of an overlap joint is not proportional to the length of the overlap. Since the adherends are not rigid and they stretch more nearest their loaded end, the generated shear stress is not uniform but peaks at the overlap ends. In addition, the offset loading causes bending of the loaded substrate, inducing peel stresses. Figure 2.4 illustrates the stresses in a single lap joint [4]. As a solution, a double lap joint has a balanced construction that is subjected to bending only if the loads on the double side are not balanced [3].

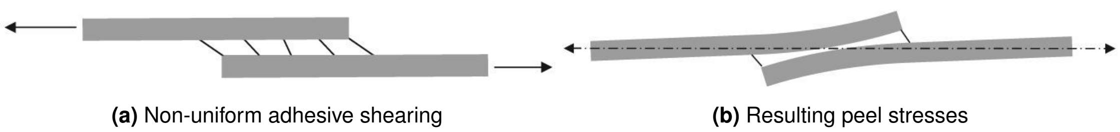
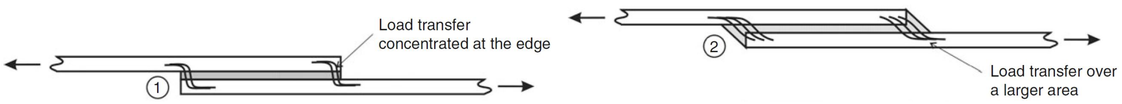


Figure 2.4: Stress distribution in a single lap joint [4]

However, spew fillets may be utilized to reduce the discussed stress concentration of a single-lap joint. Therefore, modification of the joint end geometry with a spew fillet spreads the load transfer over a larger area and gives a more uniform shear stress distribution [5]. A schematic representation of the different load transfer is given in Figure 2.5.



(a) Single lap joint without fillet **(b)** Single lap joint with fillet

Figure 2.5: Load transfer in a single lap joint [5]

If the adherends are too thick to design simple overlap joint, butt joints can be designed. A butt joint is a design where two adherends are attached to each other by placing their ends together without any special shaping. However, these joints are not able to withstand bending forces because under such forces the adhesive would undergo cleavage stress. Therefore, those joints are generally unsatisfactory [3].

A further discussion of joint designs goes beyond the scope of this research. The interested reader is referred to *Adhesives technology handbook* [3] by S. Ebnesajjad and to *Handbook of adhesion technology* [5] by L. da Silva et al.

2.2.5 Surface treatments

As adhesive bonding is a surface phenomenon, preparation of the contact surface is vital for strong bond formation. Surface preparation is carried out to render the adherend surfaces receptive to the development of strong, durable adhesive joints. It is desirable to expose the adherend surface directly to the adhesive, without an intervening layer [29].[5] Furthermore, surface treatment is desired to maximize the degree of intimate molecular contact [30].

Surface treatment of metals

It is not possible to obtain a strong adhesive bond without cleaning the metal surface. Metals have high energy surfaces and absorb oils and other contaminations that may be present in vapour form in the ambient air. A list of steps may be taken to prepare metal surfaces [29]:

- Cleaning (using a solvent or another chemical)
- Removal of loose materials (e.g. grit blasting)
- Improvement of corrosion resistance
- Priming
- Surface hardening

Cleaning Surface contaminants can be considered to fall within two groups: organic and inorganic materials. The removal of organic compounds can be achieved by using simple degrease processes, whereas the inorganic compounds might require a combination of degrease, desmut and in extreme cases deoxidizing [30].

[5] Examples of intervening layers are an oxide film, paint, chromate coating, phosphate coating or silicone release agent [29].

For metals, an atomically clean surface will have a positive spreading coefficient, so wetting by a subsequently applied adhesive will occur. Degreasing is the simplest method of achieving a clean surface and thereby increasing its surface free energy and spreading coefficient [30].

The simplest form of degreasing (by using organic solvents) is used as a stand-alone treatment and as the first stage in a wide variety of multistage processes. However, environmental as well as health and safety legislation is rapidly reducing the range of solvents that can be used by this method. Furthermore, some standards agencies no longer advocate the use of solvents for the degreasing and cleaning of substrates to be bonded, preferring instead detergent degreasing or alkaline cleaning [30].

Priming An adhesive primer is usually a dilute solution of an adhesive in an organic solvent applied to the adherend producing a dried film with a thickness of 0.0015–0.05 mm. Primers improves wetting, protects the adherend surface from oxidation and it helps inhibit corrosion. In addition, primers provide a more flexible manufacturing scheduling, higher reliability, more durable joints and less rigorous cure conditions [31].

Surface treatment of plastics

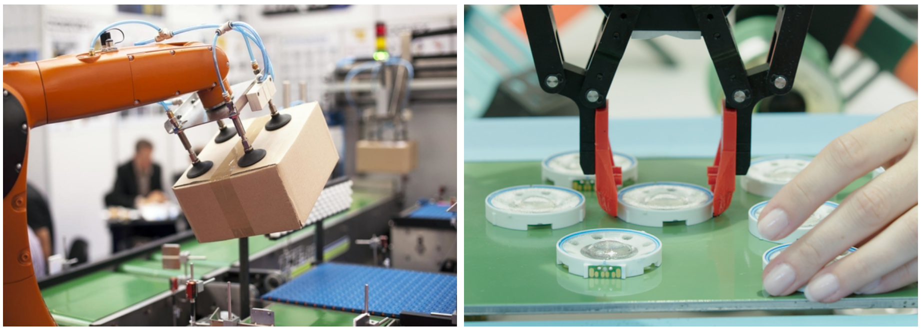
An important difference between metals and plastics is their surface energy. Polymers have inherently lower surface energy than metals and tend to form intrinsically poor adhesion bonds without some type of treatment. Treatment of plastics only impacts the region near the surface and does not alter the bulk properties of the parts. The four basics steps here are cleaning, ablation, cross-linking and surface chemical modification [29].

2.3 Grippers

An automated adhesive bonding application has to grab either a sample or a dispenser. Therefore, this section surveys the possible grippers that can be used.

Generally speaking, there are about four types of robotic grippers. The first type are vacuum grippers, which have a high degree of flexibility. Second, there are pneumatic grippers, which are popular due to its compact size and light weight. These grippers can either be opened or closed. Third, hydraulic grippers provide the most strength, but are messier than other grippers due to the oil used in the pumps. Finally, servo-electric grippers appear more and more in industrial settings because the grippers are easy to control, they are highly flexible and are also cost effective because they are clean and have no air lines [32].

Despite the better cost effectiveness of servo-electric grippers, the grippers used in this research are vacuum grippers. The main reason for this is the ability to grab a part on one face, in contrast to other grippers. This ensures that bonding can be done directly on many sides of the sample, which greatly increases flexibility. Figure 2.6 illustrates this benefit.



(a) Vacuum grippers [33] **(b)** Parallel gripper [34]

Figure 2.6: Ability to grab a part on one face

2.4 Existing applications of automated adhesive bonding processes

This section sheds light on the existing applications regarding automated adhesive bonding processes with a secondary approach to robots with more cognitive capabilities.

The main subsystems employed in this research are an automatic dispensing machine and an industrial robot. Two main variants are suitable for the planned production. On the one hand, the substrate gets fixed and the robot moves with the dispenser attached to it. On the other hand, the dispenser is fixed and the robot moves the substrate around. In this study, the latter was chosen. An additional advantage is the possibility that the robot can easily store the samples.

P. Li et al. [6] discuss a robot that has to produce reproducible samples in Section 2.4.1. These types of robots are programmed in a deterministic way and require exact control over the circumstances of the motion task. For instance, the motion of a simple pick-and-place process requires exact knowledge of the position of the object to be picked up and about the container in which the object is to be placed in. If for some reason this exact position can't be measured[6], small deviations of either the object or the container would result in process failure, as the deterministic programming of the motion is not able to deal with small variations of the environment. Therefore, some robots with more capabilities were presented afterwards [7].

Since the second research question attempts to develop a sort of quality control, it may be useful to investigate what cognitive capabilities (machine vision, reinforcement learning, etc.) are feasible. Section 2.4.2 sheds light on a study where automatic path planning in combination with a quality control is obtained with machine vision, while Section 2.4.3 achieves automatic path planning by using CAD-data. Finally, Section 2.4.4 elaborates reinforced learning, a state-of-the-art technique that is used for adapting a robot to its environment.

2.4.1 Thin-type space solar cell

The first discussed application is surveyed by P. Li et al. [6], where they presented an industrial robot used for thin-type space solar cells bonding. The used robot is not like a typical robot, instead it is based on a three-axis Cartesian coordinates' motion, where the dispenser is attached on the robot (Figure 2.7). Seeing that the radiation in outer space is over ten times higher than on earth and the temperature varies from about $-180\,^{\circ}C$ to $150\,^{\circ}C$, it was necessary to bond an anti-

[6]Because the application does not have enough sensors or their deviation is too large.

irradiation cover glass on the surface of the space solar cells. The main reasons why P. Li et al. chose to use a robot for this application is the fact that there are high requirements for the adhesive bonding. The thickness of the adhesive layer should be even and its maximum is required to be less than 100 µm. Besides, the quantity and size of the air bubbles in the middle of the solar cells also have very high requirements. Therefore, the developed robot is much more precise than humans and has the ability to follow a specifically defined trajectory [6].

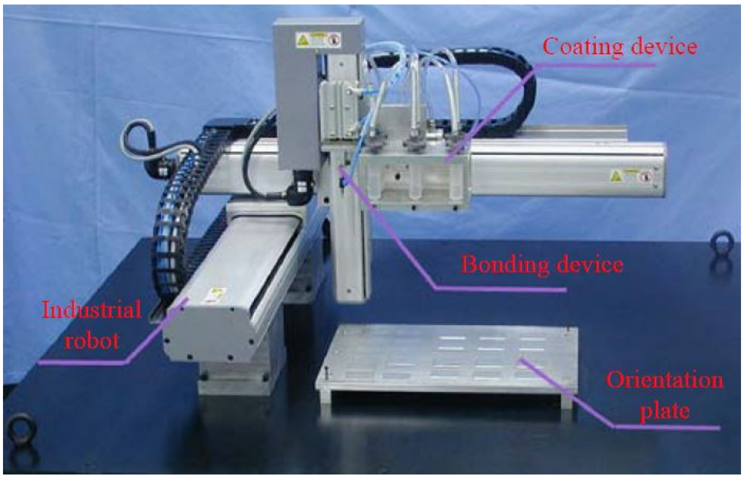


Figure 2.7: Prototype of the used three-axis robot [6]

Trajectory The path that the robot follows when applying adhesive on the whole solar cell is defined as the trajectory of bonding. An adhesive layer shape is a key factor for avoiding outflow and air bubbles. To effectively suppress air bubbles in the adhesive layer, the optimized trajectory makes use of a little higher center in the solar space cell, which forces air out. In order to get an equal adhesive outflow over the whole solar cell, the path of the dispenser starts movement every time from the center of the solar cell and moves to every point located on the edges of the adhesive layer shape [6]. Figure 2.8 illustrates the optimized trajectory.

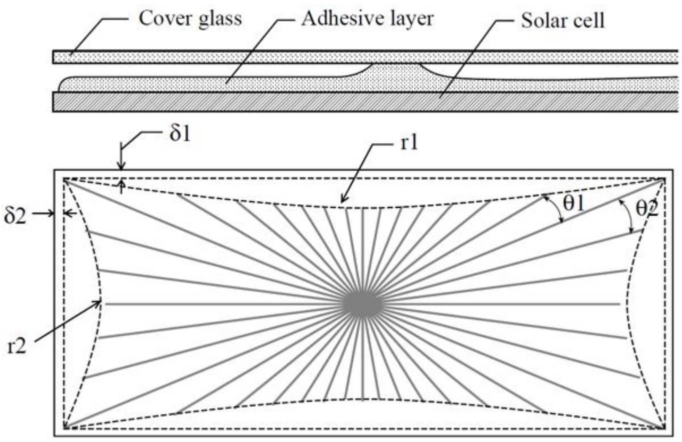


Figure 2.8: Optimized trajectory of bonding [6]

2.4.2 Adhesive coating robot based on visual servo

A second existing application is given by Z. Yang et al. [35], where their approach is to convert a captured image into a feature vector. The intelligent adhesive-coating robot consists of a CPU using machine vision and an adhesive-coating robot. Machine vision has the capabilities of image capture, workpiece identification, generation of an adhesive-coating path, visual-servo feedback and adhesion quality detection. The adhesive-coating robot has the capabilities of accurate servo location and adhesive-coating under constant pressure.

The key technology is to determine the existence and similarity of a workpiece. After image capture, the image is compared with a standard image by constructing the matching feature vectors. If the Euclidean distance between the identified picture and the standard picture is lower than a certain value, the workpiece is recognized and the CPU starts some sub-processes. A first sub-process identifies the robot trajectory by real-time analysis of image information. The identified trajectory gets compared with the desired trajectory, followed by the computation of the prediction trajectory and modifies the robot motion with a closed-loop control system. The second sub-process ensures adhesion quality control, since a broken adhesive curve is a severe quality problem. The image gets processed by threshold segmentation to extract the adhesive curve information, after which edge detection is performed on the processed image. Once the edges are detected, a closed curve of adhesion is judged [35]. This approach of image segmentation and edge detection for quality control is widely used in other adhesion processes ([36]) as in many other fields of production ([37], [7]).

2.4.3 CAD-based adhesive spray system

In this third example, where an adhesive spray has to be applied on shoe outsoles, automation was for a long time not possible due to the high amount of different kinds of shoes. To overcome this absence, it is necessary to generate robot working paths automatically according to the kind, the size and the distinction between the left or right of a shoe. J. Y. Kim [38] presents a method to generate three-dimension robot working paths based on CAD data with a setup where the dispenser is attached to the end of a robot arm. In the case of shoe outsoles, the three-dimensional data of an outsole outline including x, y, z Cartesian coordinate values and an orientation θ value are extracted from a two-dimensional CAD drawing of a shoe outsole. Subsequently, the CAD drawing has to be transformed in to the robot coordinate frame in order for the robot to know where the shoe outsole is located. Next, the number of robot working points has to be determined. Concretely, this means that the number of points that a robot passes through must be determined, because a working path is generated on the basis of the working points of an outsole outline. More working points makes the robot working accuracy higher, but makes working time longer.

Since the adhesive spray application is based on the setup where the dispenser is attached to the end of a robot arm, the nozzle end position and orientation has to be determined. Although this can be determined based on the 3D data, adhesive characteristics vary for example with viscosity, due to the fact that the ambient temperature varies. Since the nozzle has to be placed on a specified distance from the surface, nozzle parameters, adhesive characteristics and spray pressure had to be established before the nozzle end position can be specified on the basis of 3D data [38].

2.4.4 Reinforcement learning

Although the *Adhesive coating robot based on visual servo* (Section 2.4.2) is an example of a computer vision application, the robot has to be programmed manually and optimized according to the behaviour of the application. Nevertheless, R. Meyes et al. [7] presents a state-of-the-art technique termed reinforcement learning used for adapting a robot to its environment. Reinforcement learning is based on the idea to provide a robot with sensor technology that allows it to observe its environment and to complement it further by an operating agent that is able to control the robot and gather experiences about its interactions with the environment. Based on those experiences, the agent seeks to adapt its behaviour and control the robot in such a way that the motion task is performed as intended. Figure 2.9 illustrates the underlying state-action-reward principle of reinforcement learning.

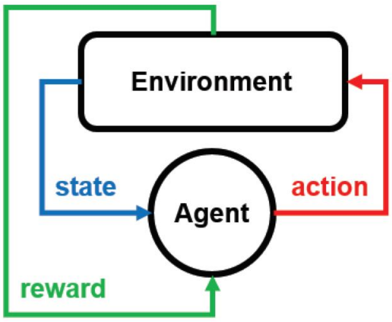


Figure 2.9: Schematic representation of reinforcement learning [7]

3
System setup

3.1 Introduction

This chapter presents an overview of the setup used in this research and describes in some detail the several subsystems. Moreover does this chapter elaborates the combination of the subsystems to establish a communication between them, along with an explanation of the samples that has been used and a presentation of the global outline. It will turn out that this chapter provides all the necessary components to answer the first research question formulated in Section 1.1: ‘Could representative samples, consisting of aluminium and plexiglass plates joined by an adhesive bond, be produced with an automated gluing process assisted by a robot?’ whereas Chapter 4 will provide a conceptual background for the second research question: ‘Could the uniformity and the curing condition of an adhesive bond be determined with a camera, by using an adhesive which colour is curing-dependent?’ Consequently, the answer to the two research questions can be investigated with the software designed in Chapter 5.

The two main subsystems elaborated in this chapter are therefore an adhesive dispensing machine and a robot, since these are the only components that are necessary to investigate the first research question.

Section 3.2 describes the specific samples that are used in this research along with the according terminology. Section 3.3 explains the positioning of the separate components relative to each other, just like the explanation of a production cycle. Subsequently, the adhesive dispensing machine and the robot are explained respectively in Section 3.4 and Section 3.5. Finally, the connections between the adhesive dispensing machine and the robot are elaborated in Section 3.6.

3.2 Samples

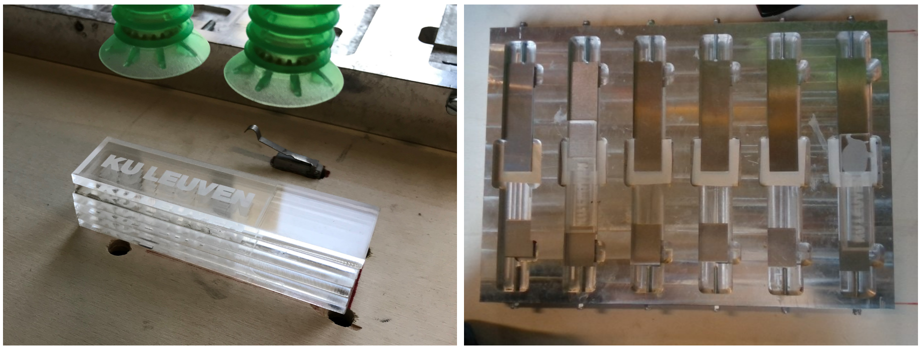
The objective of this research is to glue specific plates with each other. This study particularly investigates the adhesive bonding between small normalized plexiglass plates and aluminium plates. These plexiglass plates are referred as adherends, whereas the combination of the two plates with the adhesive bond is called a sample.

An example of an adhesive bond is shown in Figure 3.1.

Figure 3.1: Example of an adhesive bond

The adherends were taken in the beginning of a cycle from a repository, which contains six adherends on top of each other as shown in Figure 3.2a. Furthermore, a mould is used to easily create a standardized spacing between the samples in progress (Figure 3.2b). This specific used mould contains six openings, where the aluminium plates were placed. Those adherends and aluminium plates were placed at their position by hand, however, in an industrial context could this process be performed by another robot in the production line.

An other small plate is placed on the opposite side of the opening in the mould to make sure the adherend won't tilt. As a result, the adherend has to be placed between the two underlying plates with 'KU Leuven' at the top and the small free section on the left side of the text had to be bounded with the aluminium plate. Consequently, the sample starts curing which is a chemical process that hardens and toughens the bond. Once curing has finished, the robot picks up the sample from the mould to store it in a depot.



(a) Repository **(b)** Mould

Figure 3.2: Repository of adherends and mould for the samples

3.3 Global outline

The robot is placed on the robot table, which is also the main working area of the whole setup. The adhesive dispensing nozzle is attached on the robot table whereas some intermediate components like relays are mounted underneath this table.

The whole setup is shown in Figure 3.3.

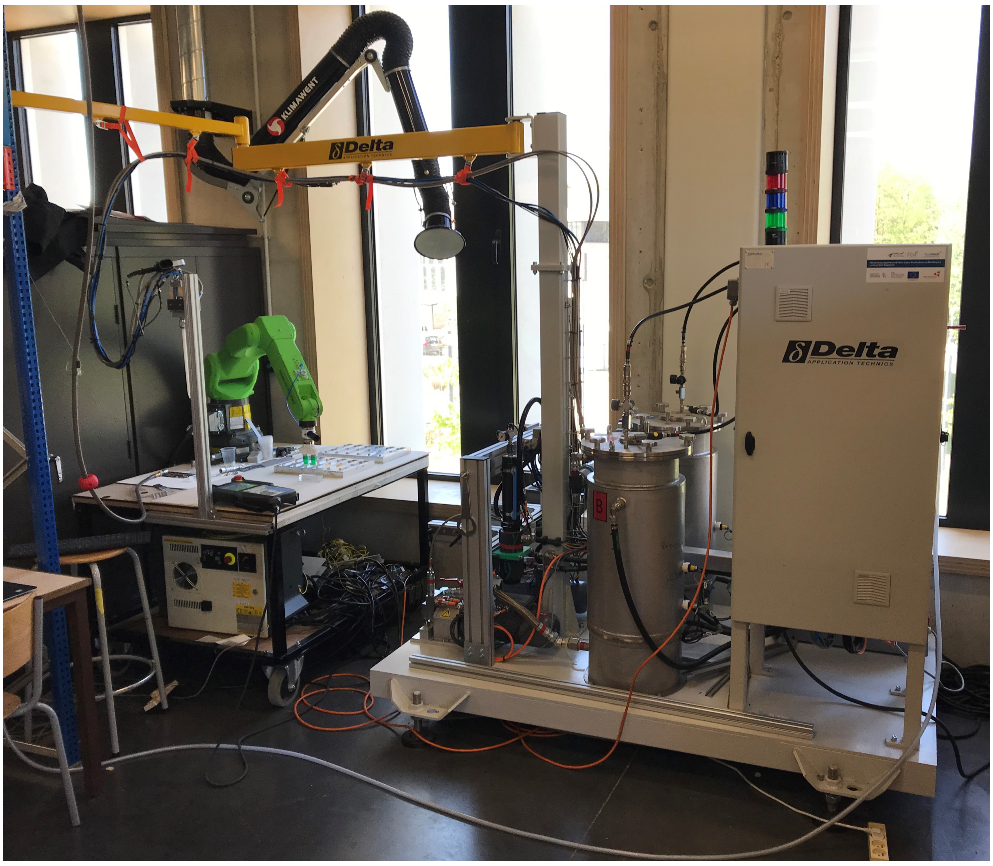


Figure 3.3: Global outline of the setup

Next, Section 3.3.1 provides a fundamental explanation of a typical production cycle, which contains the implemented cycle as well as the conceptual cycle for the sake of completeness. This fundamental explanation is necessary for a further understanding of the following sections, while Section 5.1 provides a thorough explanation of all the required steps in a production cycle.

3.3.1 Production cycle

The robot has to take an adherend from the repository with its vacuum gripper, bring it to the adhesive dispensing nozzle, attach glue on the adherend and push it on the first aluminium plate to create a sample. This cycle repeats another five times until the repository is empty, where the only main differences are the changing pick and place positions. Once the repository is empty, the mould is filled entirely.

It is desirable that the robot has no downtime, hence two moulds and two repositories are used. Once a repository is empty and a mould is filled, the other repository provides adherends for the other mould. To differentiate these two moulds from each other, the mould farthest from the adhesive dispensing nozzle is called mould A, while the closer mould is called mould B.

A second conceptual desire (which is further elaborated in Chapter 4) is the ability to pick up the samples again once they are cured[1], hence a camera has to observe the condition of the

[1] If however the distribution of the glue is not uniform or curing takes too long, the samples are refused and the robot places them in a separate box.

samples. A useful property of the glue being used is the feature that the colour changes while curing. However, these changes are only detectable with the camera that is used if it is close enough to the samples. In contrary, when the camera is relatively close to the samples, the robot would collide with the camera. The solution chosen in this research is a rotating construction that positions the camera above the mould other than the one being filled. Once the mould is filled entirely, the construction rotates, placing the camera above the mould and starts observing the condition of the samples. At the same time, loading of the other mould begins.

When a repository is not filled properly (i.e. less than six adherends provided), the cycle may go on, but only for the provided adherends. Therefore, the robot has to test whether or not its gripper holds an adherend. This small test is performed using an integrated safety button, where the button is pressed due to the extent of the adherend.[2] The integrated safety button is shown in Figure 3.4.

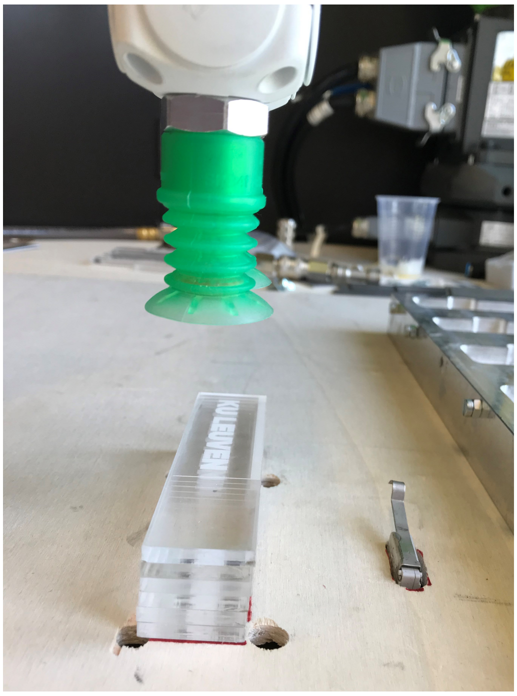


Figure 3.4: Integrated safety button

3.4 Adhesive dispensing machine

The adhesive dispensing machine DMC202 (Figure 3.5) from Delta Application Technics provides a two-component adhesive to the adherend. The main purpose of the machine is therefore to provide a properly mixed, constant amount of adhesive. Besides, the adhesive dispensing nozzle is fixed via a construction with the robot table, hence the robot has to take care of the trajectory that is being pursued.

[2]Since there was no other suited possibility to check if the gripper holds an adherend, it is assumed that adherends would not loose the gripper while moving or that the gripper would not fail to pick up an adherend when the repository provides one.

Figure 3.5: Adhesive dispensing machine DMC202 from Delta Application Technics

Section 3.4.1 explains the working principle of the adhesive machine, in particular how it transports the components of the adhesive and how the mixing of these components is performed. Section 3.4.2 elaborates on the working modes that are available on the adhesive dispensing machine as well as the associated parameters that can be measured in those modes. The actual supply of the glue on the adherend is obtained with the adhesive dispensing nozzle, which is fixed via a construction explained in Section 3.4.3.

3.4.1 Working principle

The used two components of the adhesive are resin A and resin B. These components do not cure automatically under normal atmospheric conditions, instead they cure when they interact with each other. This is why the two components are stored in separate containers, which can be pressurised if desired. These containers each have a volume of 45 l and their current level is continuously monitored. Once a first threshold level is passed, a warning occurs. If the container does not get refilled and consequently a second lower threshold is passed, an alarm takes over and the production inevitably stops.

To provide the components to the adhesive dispensing nozzle, two gear pumps are mounted in connection with the containers for taking care of the flow rate of each component. The tubes leaving the gear pumps are directed to the adhesive dispensing nozzle, where each component can be dispensed separately. A plastic mix unit can be mounted on the dispenser to obtain the desired properly mixed, constant amount of adhesive flow. The mixing of these components is obtained by creating a lot of turbulence, therefore removing welding lines as much as possible. This plastic mix unit is shown in Figure 3.6.

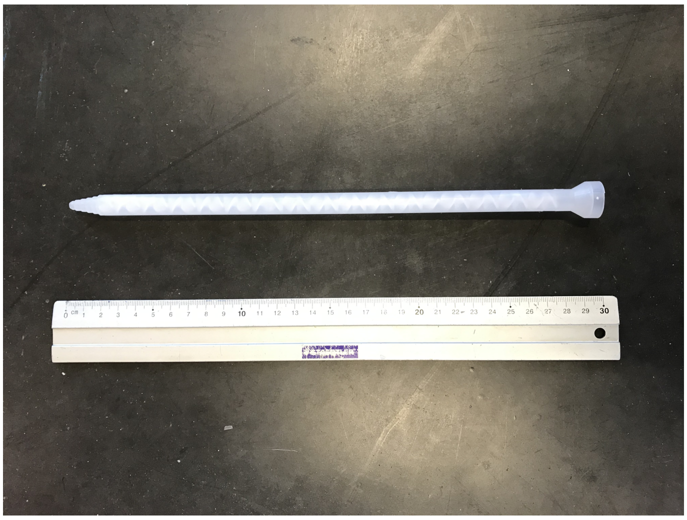


Figure 3.6: Plastic mix unit

3.4.2 Working modes

The management of the adhesive dispensing machine is done by PLC's, supplemented with some relays, fuses and differentials. In addition, a touchscreen monitor is used to set and monitor the parameters of the application. Some examples are the in- and outlet pressure, the filling level of the containers, the dosage of product A relative to B, the flow rate, etc. Another important parameter for this application is the pot life remaining time, which takes care of the time before the glue in the plastic mix unit starts curing.

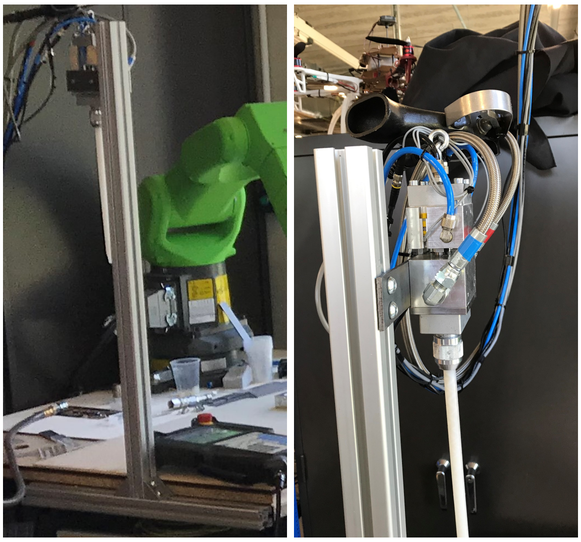
The adhesive dispensing machine makes use of the 'production' mode when producing samples while the 'set up' mode is used by the operators to tune the parameters. If a parameter exceeds its pre-limits due to some external event, a warning will occur. Nonetheless may the production continue while an operator checks the application. If however a parameter exceeds its upper limit, the production stops immediately.

3.4.3 Adhesive dispensing nozzle

The adhesive dispensing nozzle is fixed via a construction with the robot table. This construction has been made from 'MB Building Kit System' profiles, available on the campus. These profiles can easily be connected with each other with the use of T-Slot nuts.

The connection between the table and the lowest bar of the construction is achieved with long screws through a support bar from the robot table and T-Slot nuts in the lowest profile bar of the construction.

This described construction made for the fixation of the adhesive dispensing nozzle is shown in Figure 3.7.



(a) Construction **(b)** Fixation of the nozzle

Figure 3.7: Construction for the fixation of the adhesive dispensing nozzle

3.5 Robot

This section sheds light on different aspects of the six axes robot that has been used in this research, namely a Fanuc CR-7iA/L in combination with the robot controller R-30iB Mate. Section 3.5.1 elaborates the numerous safety devices associated with the robot, such as the deadman switch, the collaborative function and suchlike. In addition, Section 3.5.2 investigates the different coordinate frames used for this application as well as an explanation of the six different robot axes. Due to the fact that this robot has to grab parts with a vacuum gripper[3], Section 3.5.3 examines which type of vacuum gripper meets the requirements of the used samples. The vacuum creation that is necessary to grab parts is based on a venturi that demands pressurized air, which is delivered from the robot its internal pneumatic solenoid valve, elaborated in Section 3.5.4.

3.5.1 Safety devices

The Fanuc CR-7iA/L is a collaborative robot (cobot), meaning it has a sensor technology integrated in it which automatically makes the cobot stop after touching an object. However, this functionality can cause problems when used with more heavy products.[4] A previous application made use of relatively heavy products, hence the collaborative function was disabled at the beginning of this research. Keeping in mind that future projects may also experience problems with the collaborative function enabled and the fact that switching the function is a time-consuming activity, this function stayed disabled during the programming phase of this research. However, if this application would be used in the industry with these lightweight samples, the collaborative function would self-evidently be activated. As a result, it will be assumed that the collaborative function has been activated in this research.

[3] A vacuum gripper is identified in Section 2.3 as the most suitable gripper for this application.

[4] Products above 7 kg [39].

In addition, the robot features a lot of other safety devices beside the integrated sensor technology. To begin, there are several emergency buttons connected to the robot: one on the robot controller, one on the Teach Pendant, an external safety button connected with the adhesive dispensing machine and an unused one for a safety gate. Furthermore, the Teach Pendant makes use of a deadman switch which has to be pressed in order to allow robot movements while programming. Hence, the robot stops immediately when releasing or over-pushing[5] the switch.

Another safety device used in this robot is the Fanuc Dual Check Safety (DCS) which provides position and speed checks, safe zones and protection of expensive tools [40]. A simplified position check has been used in this research because the robot is positioned in a corner with its working area particularly in one quadrant. It is therefore prohibited that the robot moves outside of this area, hence some restrictions were imposed. However, a deep explanation and configuration of all the possibilities of DCS are beyond the scope of this thesis.

3.5.2 Robot axes - coordinate frames

The robot has a total of six movable axes, as shown in Figure 3.8, which creates a lot of flexibility. Below is an explanation of the movements of the six axes [39]:

1. Axis 1 (J1): This axis is located at the robot's base, allowing it to rotate around the central axis. The robot is able to perform rotations up to 340 degrees, but is restricted to a 90° angle in one quadrant as it is placed in a corner.
2. Axis 2 (J2): This axis provides the ability to rotate the lower arm as an elbow up to 166°.
3. Axis 3 (J3): This axis rotates the upper arm also as an elbow, extending the vertical reach of the robot, allowing for movements up to 374°.
4. Axis 4 (J4): This axis rotates the upper arm around its own axis, which is necessary to change the position from taking the sample on the upper surface to gluing on the bottom surface. Movements up to 380° are allowed.
5. Axis 5 (J5): This axis can be seen as a wrist, to tilt the vacuum gripper up to 240°.
6. Axis 6 (J6): This last axis can twist the samples to a maximum of 720°.

[5] For example due to an electrical shock.

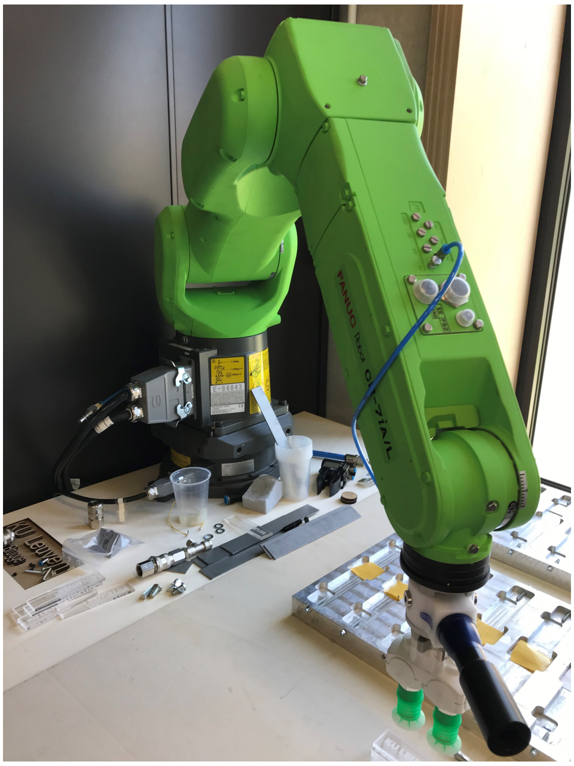
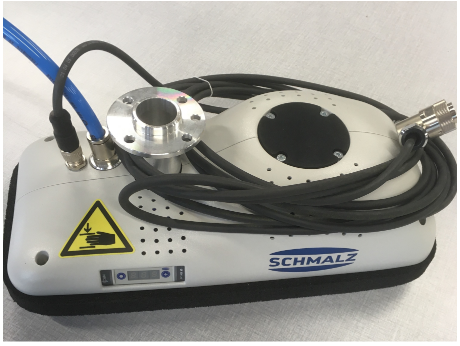


Figure 3.8: Fanuc CR-7iA/L

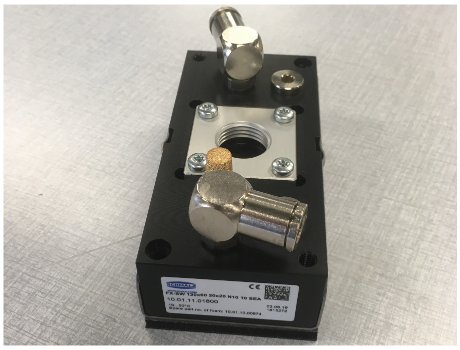
Many different coordinate frames can be defined to determine different positions of objects. The main two frames used in this study are the baselink-frame and the gripper-frame. The baselink-frame is situated at the base of the robot, with its z-axis pointing perpendicular on the robot table and the y-axis in the width direction of the robot table. The gripper-frame is situated at the end-effector of the robot (i.e. the place where the vacuum gripper is attached to the robot) with its z-axis pointing parallel to the gripper and the x-axis pointing the direction of zero degree measurement of J6.

3.5.3 Vacuum gripper

As mentioned in Section 2.3, the best grippers for this application seem to be vacuum grippers due to their ability to grab parts on one face. Some vacuum grippers were already purchased before the beginning of this research. Three different types from Schwalmz were provided: the vacuum area gripping system FXCB (Figure 3.9a), the vacuum area gripping system FX-SW (Figure 3.9b) and a starter set for configuring vacuum end effectors (VEE) (Figure 3.9c). Furthermore, a Unigripper Co/Light Mini (Figure 3.9d) was available. Table 3.1 clarifies the benefits and drawbacks of each vacuum gripper relevant to select the most suitable gripper for this application.

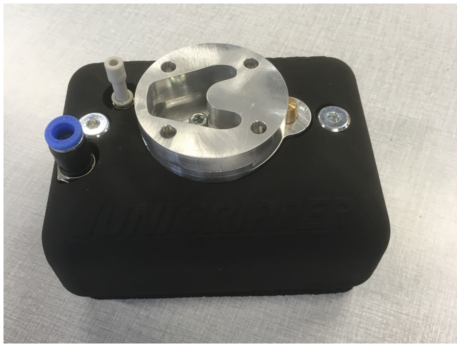


(a) Schmalz FXCB



(b) Schmalz FX-SW

(c) Schmalz VEE



(d) Unigripper CO/Light Mini

Figure 3.9: Vacuum grippers

Vacuum gripper	Benefits	Drawbacks
Schmalz FXCB [41] Contact surface: 390 cm^2	Integrated vacuum generator Vacuum monitoring Intelligent vacuum area NFC interface for data transmission	Relatively big and heavy No flexible surface
Schmalz FX-SW [42] Contact surface: 72 cm^2	Integrated vacuum generator Minimal leakage losses when cells are not in use Rapid vacuum power build-up	No flexible surface
Schmalz VEE [43] Contact surface: 14 cm^2	Flexible placing and usage, partly by suction cups High suction capacity with low air consumption	No integrated vacuum generator
Unigripper Co/Light Mini [44] Contact surface: 168 cm^2	Integrated vacuum generator Additional control box for grip indication	No flexible surface

Table 3.1: Comparison of vacuum grippers

The samples for this application were still under consideration during the first period of this research. However, it was known that samples would have a width of around 3 cm and may have some folds which creates an irregular surface. These characteristics indicate that a flexible, relatively small gripper was desired, hence the Schmalz Vacuum End Effector (VEE) was chosen.

As mentioned in Table 3.1, this Schmalz VEE does not have an integrated vacuum generator. The vacuum is therefore obtained with the use of a venturi, attached just above the gripper, as can be seen in Figure 3.9c. The compressed air is provided from the internal pneumatic valve of the robot, further elaborated in Section 3.5.4, at a pressure of eight bar. Experiments conducted on this gripper indicated that it has the ability to hold samples up to a weight of 538 g with two suction cups, each having a diameter of 3 cm. Besides, it is important to note that adherends with a width of slightly less than 3 cm can still be picked up since the suction cups embrace the adherends, therefore preventing the leakage of the created vacuum.

The magnitude of the underpressure[6] gets calculated as well since this may be useful for further extensions. With the formulas provided in Equation 3.5.1 gets the underpressure calculated in Equation 3.5.2.

$$\begin{aligned} p &= \frac{F}{A} \\ F &= m \cdot g \\ A_{circular} &= \frac{\pi \cdot d^2}{4} \end{aligned} \tag{3.5.1}$$

$$\begin{aligned} p_{under} &= \frac{0.538\,\mathrm{kg} \cdot 9.81\,\mathrm{m/s^2}}{2 \cdot \frac{\pi \cdot (0.03\,\mathrm{m})^2}{4}} \\ \Leftrightarrow p_{under} &= 3733\,\mathrm{Pa} \end{aligned} \tag{3.5.2}$$

The working principle of a venturi can be explained with Figure 3.10, where the compressed air is supplied through connection A. This air gets accelerated and compressed until it reaches the end of the nozzle. After passing through this nozzle, the accelerated air slows down again, creating a vacuum in chamber B due to a pressure drop. Hence, air is drawn through the vacuum connection D, whereas the aspirated and compressed air escapes through the silencer [8].

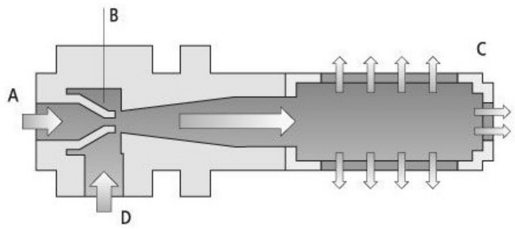


Figure 3.10: Vacuum generator - Venturi principle [8]

This explanation is ultimately derived from Bernoulli's incompressible, non-viscous flow equation shown in Equation 3.5.3 [45]. Bernoulli's equation may be used since the density of the air stays constant through the venturi.

$$p + \rho \cdot g \cdot h + \frac{1}{2} \cdot \rho \cdot v^2 = constant \tag{3.5.3}$$

Even if the venturi above the vacuum gripper is placed vertical, the height difference between the entrance and the exit is negligible. Therefore, it can be derived that if the velocity from A to B rises, the static pressure drops in chamber B.

This underpressure could even be calculated with the Bernoulli equation if the flow rate of the pressurised air was known. However, these calculations may suffer from inaccuracy due to high losses in the vacuum generator.

[6]The terms underpressure and vacuum can be used interchangeably.

3.5.4 Internal pneumatic solenoid valve

The Fanuc CR7-iA/L has three internal double solenoid valves in its fourth arm which makes it more convenient to program the robot. Important to note is that the robot uses a 5/2 solenoid valve instead of a more flexible 5/3 valve, hence there is no closed center position meaning either the first or the second air supply is under pressure [39]. The principle of a 5/2 solenoid valve is shown in Figure 3.11 .

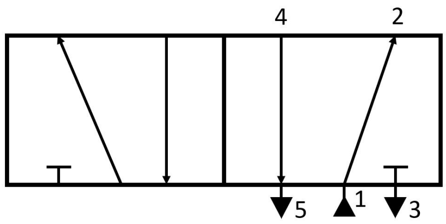


Figure 3.11: Principle of 5/2 solenoid valve

The air supply for the vacuum gripper is connected with port 4 from Figure 3.11 while port 2 is closed with a screw since the vacuum gripper does not consume pressurised air when not in use. On the other hand, one can notice that most pneumatic parallel grippers can either be opened or closed which requires pressurised air in both states. The air supplies on the fourth arm of the robot are normally just used with grippers, hence in all likelihood is this the reason why Fanuc has chosen to use the cheaper 5/2 solenoid valve instead of a 5/3 valve.

Those internal solenoid valves can be toggled straightforward with switching 'robot output RO1' in the robot program as further explained in Section 5.1.

3.6 Connections between the adhesive dispensing machine and the robot

The main program will run on the robot controller, which implies that there is a need for connections with the other machines. The connection between the robot and the adhesive dispensing machine is elaborated in this chapter since this connection was actually implemented during this research. On the other hand, the connection between the robot and the Raspberry Pi is explained in Section 4.3 as this is studied on a conceptual level.

The objective was to link the robot and the adhesive dispensing machine with a maximum of six wires, since it is desirable that the second connector remains free for future extensions. Moreover, there were three functionalities that had to be obtained by linking the machines. The first two connections are the linkages of the emergency buttons. If the emergency button on the adhesive dispensing machine is pressed, the robot may not move under any circumstance and vice versa. These connections are explained respectively in Section 3.6.1 and Section 3.6.2. The third connection provides the robot with the ability to control the adhesive dispensing nozzle, which is further elaborated in Section 3.6.3.

3.6.1 Emergency button from the adhesive dispensing machine to the robot

There is a pre-installed possibility to send the emergency button from the adhesive dispensing machine to other devices with the emergency button ‘ESTOP1’ (Figure 3.13) which makes a short circuit in operation and is open in emergency. However, the robot requires duplicate external safety signals as shown in Figure 3.12 from the robot controller R-30iB Mate manual. Because of the objective to link the robot and the adhesive dispensing machine with a maximum of six wires, keeping in mind that other linkages has to be made, the duplicate safety signal is obtained with relays. It is important to note that this alternative way is supported by Fanuc [39]. Figure 3.13 shows this linking of the emergency button from the adhesive dispensing machine to the robot.

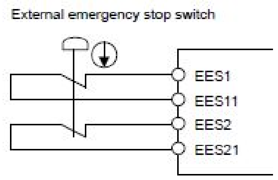


Figure 3.12: Mandatory circuit external emergency button [9]

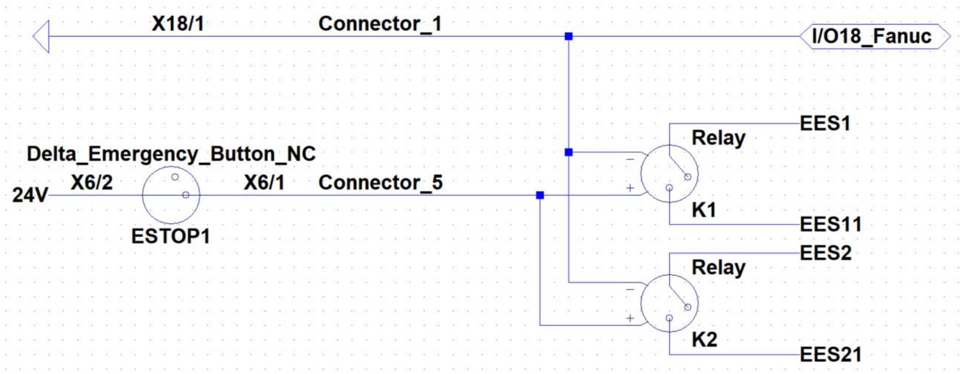


Figure 3.13: Linking of the emergency button from the adhesive dispensing machine to the robot

The relays have been placed underneath the robot table with two incoming wires from the adhesive dispensing machine and the four outgoing wires were sent to the emergency stop board in the robot controller.

3.6.2 Emergency button from the robot to the adhesive dispensing machine

The adhesive dispensing machine has pre-installed unused emergency inputs that can be received from other devices. These support duplicate safety signals as well as single ones. The emergency button of the robot ‘ESTOP2’ also makes a short circuit when in operation and is open in emergency, which is directly connected with the pre-installed emergency input of the adhesive dispensing machine via PLC 30A3 input DI1. This linking of the emergency button from the robot to the adhesive dispensing machine is shown in Figure 3.14.

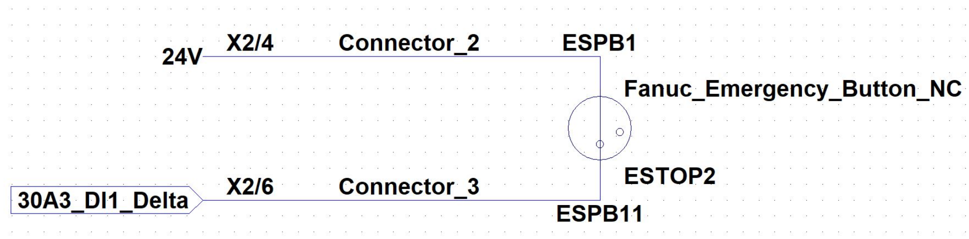


Figure 3.14: Linking of the emergency button from the robot to the adhesive dispensing machine

3.6.3 Connection between the robot and the adhesive dispensing nozzle

The robot has to communicate with the adhesive dispensing nozzle to dispense glue when the robot places an adherend under the nozzle. This communication is established with the use of the Fanuc I/O link, where DO121 triggers the relay 46K7 that bridges the extrusion request of the adhesive dispensing gun to trigger PLC 30A10 DI6. This triggering of PLC 30A10 DI6 eventually controls the gear pumps to dispense glue. This circuit is shown in Figure 3.15.

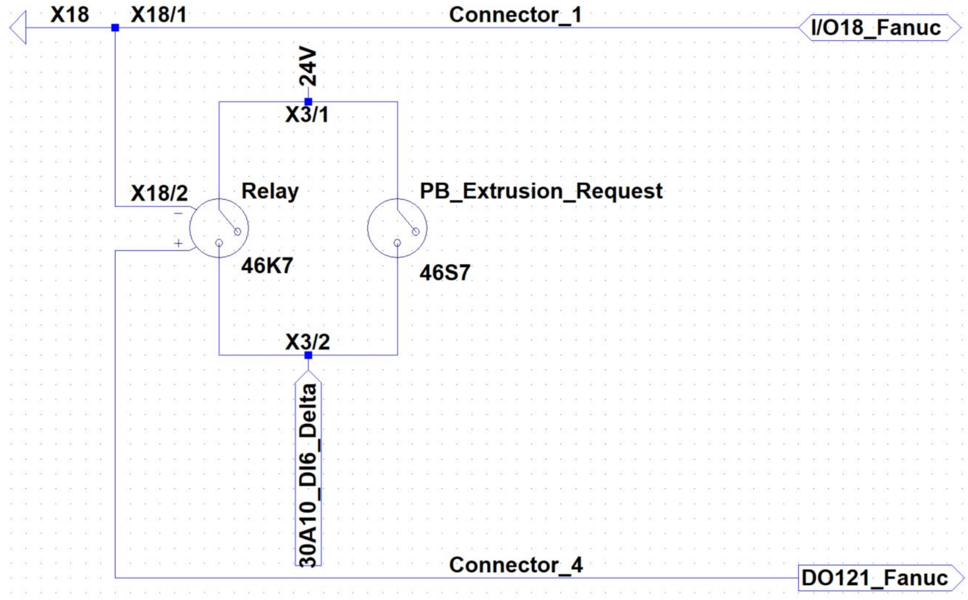


Figure 3.15: Connection between the robot and the adhesive dispensing nozzle

The corresponding suitable internal wiring circuits from the adhesive dispensing machine are attached in Appendix A. Furthermore, the usage of the in- and outputs of the Fanuc I/O link are attached in Appendix B.

3.7 Conclusion

The global outline is configured as shown in Figure 3.3, which combines the robot and the adhesive dispensing machine. The emergency buttons of these subsystems has been connected, as well as an establishment of an extrusion request from the robot to the adhesive dispensing machine.

Moreover, the vacuum gripper Schmalz Vacuum End Effector has been chosen as the best suitable vacuum gripper, mainly because of its flexibility.

It turns out that this chapter has provided all the components that are necessary for the investigation to the first research question. However, there was only one compressed air supply and it was mandatory to provide both the robot and the adhesive application with compressed air to commence the production. Therefore, there had been waited to produce samples while in the meantime the investigation to the necessary components of the second research question began.

4

Conceptual work — Vision capabilities

4.1 Introduction

The COVID-19 outbreak threw a spanner in the work for the elaboration of the second research question: 'Could the uniformity and the curing condition of an adhesive bond be determined with a camera, by using an adhesive which colour is curing-dependent?' The natural decision has therefore been made to investigate this second research question conceptually, meaning that the setup has been modelled in a CAD-environment (Siemens NX 12) and that specific connections between the robot and some conceptual components are described.

Section 4.2 sheds light on the different components that are desired to obtain a quality control on the samples. In addition, Section 4.3 explains the conversions that are mandated to establish a connection between those components and the robot.

4.2 Vision capabilities

The quality and curing condition of the samples will be captured with a camera that sends this data to a Raspberry Pi where a script determines whether or not the samples are well cured. If the program detects that the distribution from the glue is not uniform or curing takes too long, the samples are refused and the robot places them in a separate box.[1] Otherwise, if the program detects that the samples are cured within a certain period, unloading of the mould starts. However, there is a restriction that has to be taken into account. The quality of the camera is too low to make a good analyses of the samples if the camera is mounted above the robot's working zone. Hence, the camera has to be mounted somewhere within this working zone of the robot. Unfortunately, two new problems arise with this setup. Since the robot has to place adherends in the mould, keeping

[1] An extension could be to keep track of the percentage of refused samples. If these refused samples are only a small fraction of the total, they should get classified as random errors. If however a larger fraction is refused, the samples should be classified as systematic errors, which could indicate a problem caused by for example wear, changing in dosage and suchlike.

in mind it only has six axis, the robot would collide with the camera. Furthermore, to obtain the good quality that is desired, the camera can only behold one mould. To solve these problems, a construction was made that rotates the camera from one mould to another with the use of a servomotor.

Section 4.2.1 provides the specifications of the used camera as well as an elaboration of the minimum required height to behold a mould. Subsequently, Section 4.2.2 investigates the construction that is desired to position the camera. Section 4.2.3 eventually assembles the conceptual construction into the existing setup by using a virtual CAD-environment.

4.2.1 Camera

The camera that has been provided for this research is an Intel® RealSense™ D415 which provides 90 frames per second at a resolution of 1280 x 720 pixels [46]. However, the frame rate of 90 frames per second is exaggerated for this research since curing elapses several minutes, hence some frames could be dropped. This dropping may also ease the work for the Raspberry Pi.

Besides, the camera angle is 72° for the length and 65° for the width [46]. Keeping in mind that the camera should observe the whole mould with dimensions of 36 x 25 cm, the minimal distance between the camera and the mould can be derived with Equation 4.2.1, proving it should be greater or equal than 24.8 cm.

$$\min\left\{ height \,\middle|\, \begin{array}{c} \tan\frac{72^\circ}{2} \geq \frac{36\,\mathrm{cm}/2}{height} \\ \wedge \tan\frac{65^\circ}{2} \geq \frac{25\,\mathrm{cm}/2}{height} \end{array} \right\} = 24.8\,\mathrm{cm} \tag{4.2.1}$$

4.2.2 Camera mounting

The camera is mounted on a construction similar to a tower crane, as shown in Figure 4.1. Just like with tower cranes, trussed beams were used to obtain high stiffness in combination with light weight. Those trussed beams consist of four outer bigger beams with alternating oblique beams between them to provide stiffness. The upright beam is 45 cm high to provide the minimum desired 24.8 cm, taking into account mould thickness, thickness of the camera and the width of the upper beam. The mould itself has a width of 25 cm, hence an upper beam length of 30 cm has been chosen to allow some slack.

A benefit of this construction is that it only requires a single motor which turns the whole construction from one mould to another. However, bending of the upper beam and suchlike increases the inaccuracy of the camera position. Therefore, an additional step in the program is necessary to extract the mould from the image, which creates a standardized image.

Another type of construction had been conceived to overcome this additional ‘extraction’ step, which would consist of two degrees of freedom (dof’s). The idea is that the first dof is obtained by moving the whole construction from one mould to another with wheels. Consequently, once the construction has been positioned above a mould, a second motor could transport the camera to behold one of the six samples at a time, which would increase the resolution of the pictures of the samples. On the other hand, since curing is a continuous process and the camera is only capable of beholding one sample at a time, the flexibility of the construction would decrease. Moreover, two motors are required, which would decrease the simplicity of the construction.

As a result, the rotating construction (Figure 4.1) has been chosen as the best trade-off between accurately placing the camera above a mould and the simplicity of the construction. However, extracting the mould from the image is necessary in this setup, which is further elaborated in Section 5.2.

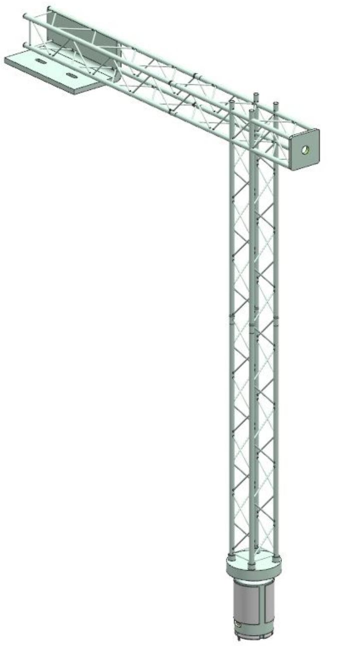


Figure 4.1: Camera mounting

The fact that the mould gets extracted does not alter the demand for a balanced construction. It is still desired to obtain as little moment as possible at the base of the construction to minimize the stresses that would arise due to bending. This desire is satisfied with a prominence in the upper beam where weights can be attached with the use of an M5 bolt, to restore the balance.

The camera can be mounted on the other side of the upper beam by using two slotted holes. Some free space has been left between the upper beam and the top surface of the mounting for the required nuts.

A critical place in this construction is the connection between the upright and the upper beam. This transition has to transfer the loads and moments as good as possible with little internal stresses. A double trussed network has been used for this transition, as shown in Figure 4.2.

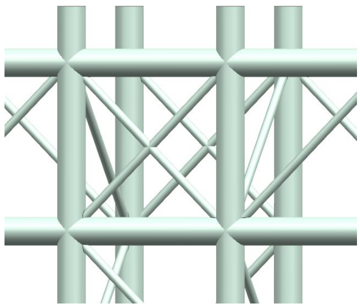


Figure 4.2: Double trussed network

It is desired that the camera mounting can be printed on the KU Leuven campus in Bruges, where the available 3D printer is a Stratasys F120 with a maximum printing volume of 254 x 254 x 254 mm [47]. These printing dimensions violates the dimensions of the construction, hence modifications were required. However, neither the upper nor the upright beam were short enough to be printed at once. Moreover, the connection between the upright and the upper beam can not be obtained afterwards due to the double trussed network used for this transition. The solution selected in this research involves breaking the construction down in three pieces, one containing the farthest part of the upper beam (Figure 4.3a), another containing the double trussed network (Figure 4.3b) and finally one with the lower part of the upright beam (Figure 4.3c). These parts are showed in Figure 4.3.

(a) Farthest part of the upper beam **(b)** Part with double trussed network **(c)** Lower part of the upright beam

Figure 4.3: Parts of the camera mounting

These parts have to be assembled afterwards. A rigid connection can be obtained with the use of an additional prominence on one connection side, allowing the parts to slide over each other. To make sure the parts do not loosen due to eventual vibrations or forces, some glue is applied on the prominence. This connection is shown in Figure 4.4.

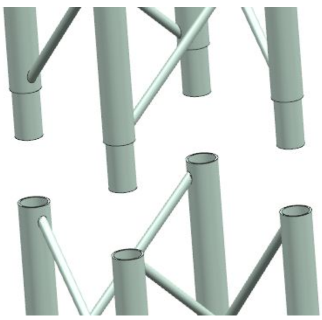


Figure 4.4: Rigid connection by sliding parts

Finally, this construction has to be assembled on the servomotor with a motor plate which is shown in Figure 4.5. The four outer beams slide in the appropriate holes, in combination with some glue, to establish the connection. Furthermore, bearings may be used to provide a smooth rotation of the motor plate. However, the whole technical elaboration goes beyond the scope of this research.

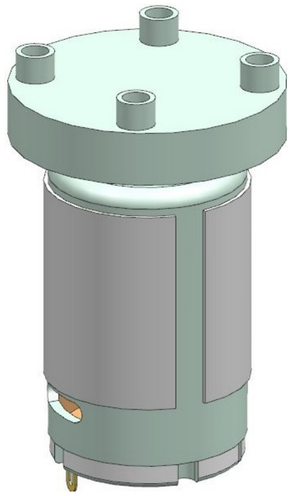


Figure 4.5: Motor plate

The Stratasys F120 3D printer supports the materials ABS-M30™, ASA and SR-30 [47]. The material choice when actually manufactured is highly dependent on the materials available on the campus.

4.2.3 Conceptual setup

The whole setup has eventually been drawn in a CAD-environment to improve the visual representation of the setup, as can be seen in Figure 4.6.

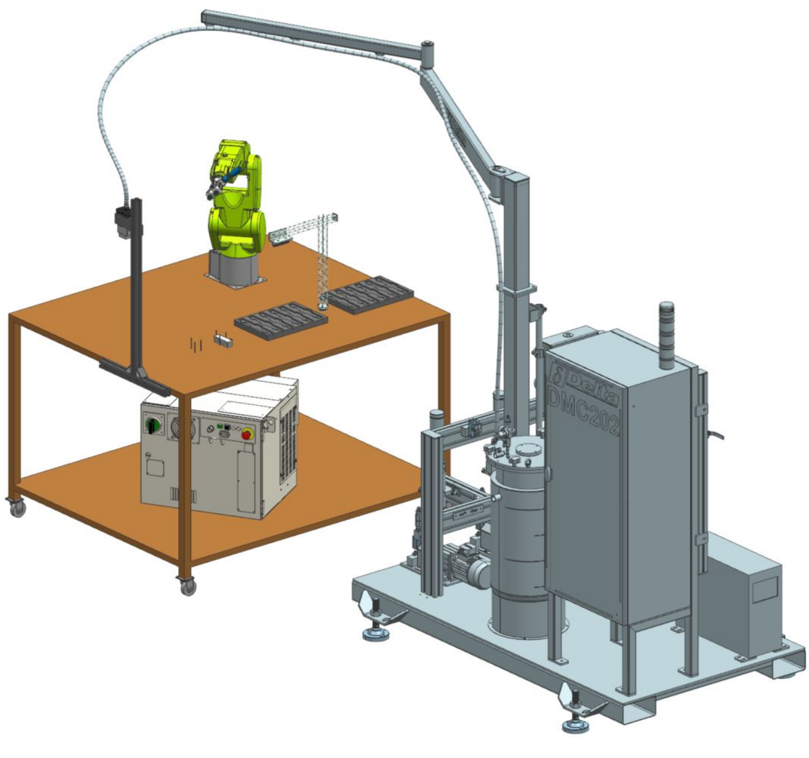


Figure 4.6: Representation of the conceptual setup

This conceptual setup contains all the components from the practical setup, ranging from the robot and the adhesive dispensing machine to the construction of the adhesive dispensing nozzle and the conceptual camera mounting. Moreover, small but crucial components like the repository, the mould, the integrated safety button and the vacuum gripper are modelled as well to provide a complete representation.

The layout of the conceptual setup is clearly visualised in Figure 4.7.

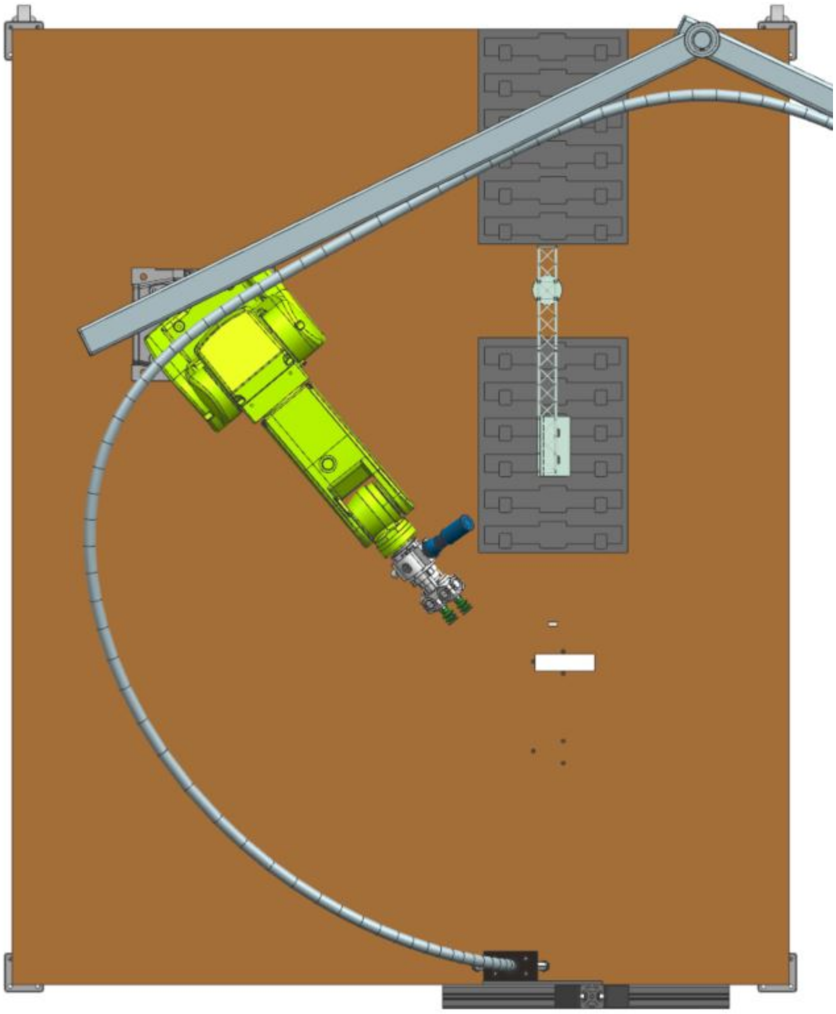


Figure 4.7: Layout of the conceptual setup

4.3 Connection between the Raspberry Pi and the robot

The Raspberry Pi, in combination with the camera, will be used to detect if the samples are cured or if they have to be refused. This information is sent through a connection established between the Fanuc I/O link and the I/O's from the Raspberry Pi. However, there is a difference between those connections and the previous connections of Section 3.6. The Raspberry Pi handles its in- and outputs at 3.3 V, whereas the robot operates at 24 V. This transformation between 3.3 V and

24 V is obtained with the use of an optocoupler, which has the same functionality as a relay but does not use moving parts. An optocoupler has therefore a much shorter switching time, though its main advantage is the galvanic isolation it provides. The input consists of a LED that turns on when applying an input voltage, after which a photo transistor makes a short circuit. The schematic representation of an optocoupler is given in Figure 4.8.

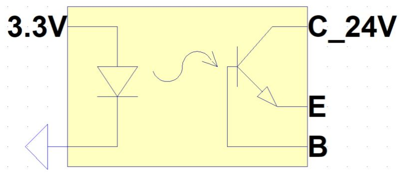


Figure 4.8: Schematic representation optocoupler

A photo transistor is a component derived from a bipolar transistor, which possesses three semiconductor layers (a base, an emitter and a collector) either NPN or PNP, with a relatively thin base layer. If a forward base-emitter voltage is applied to an NPN bipolar transistor, a recombination of the holes and electrons causes a base current flow. If hereupon the collector is connected to a positive supply, a large number of electrons are allowed to pass directly from emitter to collector. In the case of a photo transistor is the base not electrically connected, instead base current is generated by light that falls directly on the base-emitter junction. This action provides current gain which directs the 24 V to the robot [48]. The same process works the other way around too if an output of the robot has to be sent to the Raspberry Pi.

The connections that should be made between the Raspberry Pi and the robot are divided in two separate sections. On the one hand, Section 4.3.1 elaborates the connections that should be made from the robot to the Raspberry Pi. On the other hand, Section 4.3.2 explains the desired connections from the Raspberry Pi to the robot.

The specific in- and outputs that have been used by the Fanuc I/O link are defined in Appendix B, as well as the I/O's of the Raspberry Pi in Appendix C.

4.3.1 Connections from the robot to the Raspberry Pi

The camera mounting construction will have three valid positions. The first and third position provide the camera respectively above mould A and mould B, whereas the second position is a rest position where the construction turns away from the robot table to provide the robot as much room for movements as possible. The construction should be in its rest position the moment that the robot is loading mould A. Once this mould is filled and the robot would start loading mould B, the construction rotates to position the camera above mould A.

Once the construction is positioned above a certain mould, the detection of the uniformity and curing condition of the samples starts as further elaborated in Section 5.2.

As a result, the connection from the robot to the Raspberry Pi requires two wires so the desired position of the construction can be sent parallel in binary code. In addition, a third wire is used as a control wire to confirm that the robot has successfully received certain information from the Raspberry Pi, as further explained in Section 4.3.2.

4.3.2 Connections from the Raspberry Pi to the robot

The program that runs on the Raspberry Pi has to detect which samples in the mould are successfully cured and which ones should be refused. Once all the samples are cured or the maximum curing time has expired, the Raspberry Pi send a five second pulse through all the six outputs.[2] If the robot confirms that it has received these pulses, the six outputs of the Raspberry Pi sends the condition of their sample (refuse or store). Subsequently, the construction rotates to the other mould and the robot starts unloading the mould as desired.

The actual position of the camera construction must be communicated with the robot to prevent collisions between the robot and the camera. This is done in a similar manner as used in Section 4.3.1 by sending its position in binary code with two wires.

4.4 Conclusion

A rotating construction (Figure 4.1) seems the best trade-off between accurately placing the camera above a mould and the simplicity of the construction, since there is only one motor required in this setup. However, this construction brings a necessary additional step in the program, which extracts the mould from the image to create a standardized image.

Another item that should be taken into account is the fact that the Raspberry Pi and the robot can not communicate directly with each other, seeing that the Raspberry Pi operates at 3.3 V while the robot operates at 24 V. An optocoupler is therefore used to obtain this transformation, with its main advantage the galvanic isolation it provides. With the use of optocouplers, numerous connections can be established to communicate the conditions of the samples, the desired position of the rotating construction and many more.

Chapter 5 elaborates the vision program that would be used in combination with the discussed construction, although the necessary components for the investigation of the second research question are only worked out on a conceptual level. In addition, Chapter 5 explains the robot program that is necessary to answer the research questions.

[2] This pulse through all the six outputs helps detecting eventual broken lines.

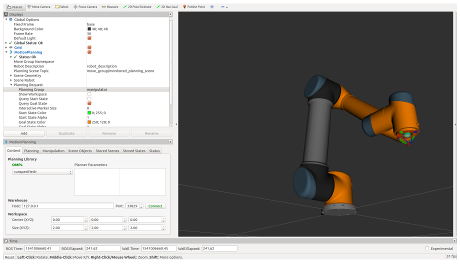
5 Program

The main program runs on the robot, which receives and sends respectively inputs and outputs. This robot program is responsible for moving the robot end effector from one place to another while potentially carrying a sample. This main program is first elaborated in Section 5.1. A second program has to determine the quality of the samples by using a camera. This program makes use of the coding language Python and is explain in Section 5.2.

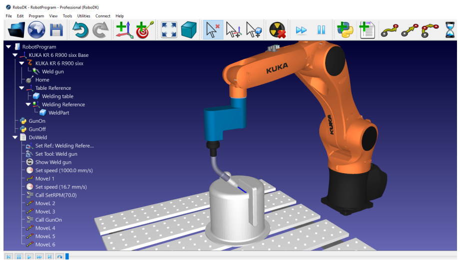
5.1 Robot program

The robot processes six samples to load one mould entirely, where the only main differences between the six samples are the changing pick and place positions. Though the robot has to run six times through long series of steps, the program should stay comprehensible.

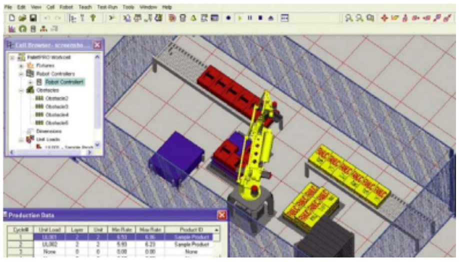
A first idea was to program these robot movements in a free middleware called ROS™ (Figure 5.1a), which allows a more dynamic approach with programming in a virtual environment. With ROS, it is possible to perform for example a quality check and feedback the robot arm upon these results so the quality of the samples may be rectified. However, this specific robot starts to work very slowly when receiving feedback, hence this approach had to be abandoned. Another approach was to make use of RoboDK (Figure 5.1b), which unfortunately also didn't work out since the communication through TCP/IP could not be established. Roboguide (Figure 5.1c), on the other hand, is the software of Fanuc itself to control the robot in a virtual environment, but turned out to be too expensive. Eventually, a more static approach with the Fanuc TeachPendant (Figure 5.1d) has been used for programming. Besides, it has to be noted that ROS, RoboDK and Roboguide are software programs that have to be installed on a separate computer while the TeachPendant is a peripheral device directly connected with the robot controller. Figure 5.1 gives an idea of the different programming environments while Figure 5.2 presents the Fanuc TeachPendant.



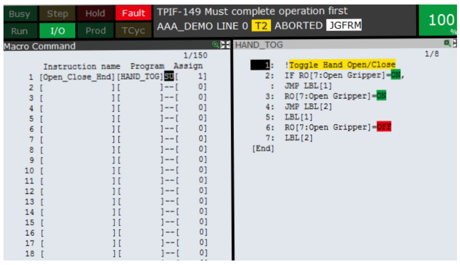
(a) ROS environment [49]



(b) RoboDK environment [50]



(c) Fanuc Roboguide environment [51]



(d) Fanuc TeachPendant environment [52]

Figure 5.1: Different programming environments

Figure 5.2: Fanuc TeachPendant

Since the robot runs every time through an almost identical path, this path has been hard-coded with fixed position registers through which the robot end effector moves every cycle. The difference each cycle is present in the changing pick and place positions. These changes were made possible with the use of double registers, where the changing picking and placing points are recorded in position registers and a counter in an integer register defines the next starting position register. The example in Figure 5.3 clarifies this technique, with the statement 'J PR[R['1:counter']]' representing that the robot end effector should move to the position register with index R['1:counter'].

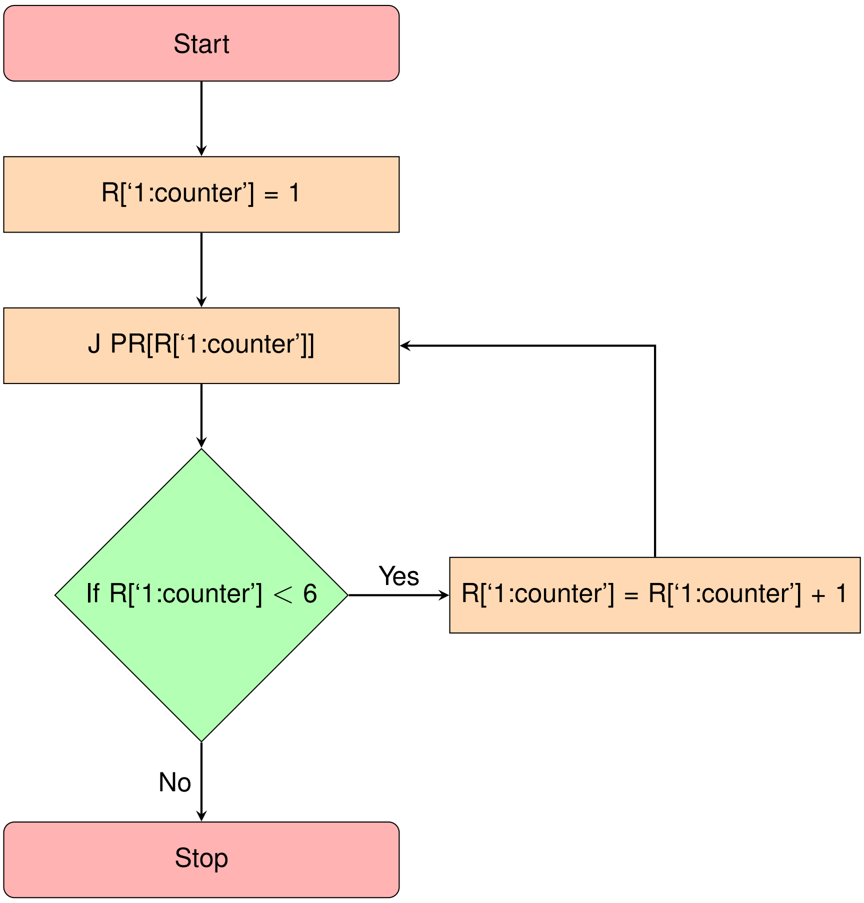


Figure 5.3: Example double registers

The position registers (PR[1], PR[2], . . . , PR[6]) do have to be initialized before running the script with the desired coordinates, whereas the integer register (R['1:counter']) gets initialized at one. Consequently, the robot end effector moves to the coordinate defined in the first position register. Once arrived at this position, the counter gets incremented and the robot end effector moves to the second position. This process conveniently iterates over the six positions, providing a flexible program by using double registers.

Another important concept for programming this robot is the desired precision of the points. If a point is defined for example to avoid an obstacle, the point does not have to be passed exactly, a rounded off movement may obtain the same desire while saving time. This can be imposed in the program with using 'CNT X' where X is the allowed rounding off radius. Figure 5.4 illustrates this concept. A subsequent concept defines the way of moving from one point to another, which can be either by joint movements or with linear movements. When using joint movements, all axes will calculate what angle they should rotate and then moves independent from each other to the desired angle. Linear movements are used when the robot has to move in a straight line and is therefore denoted in mm/s.

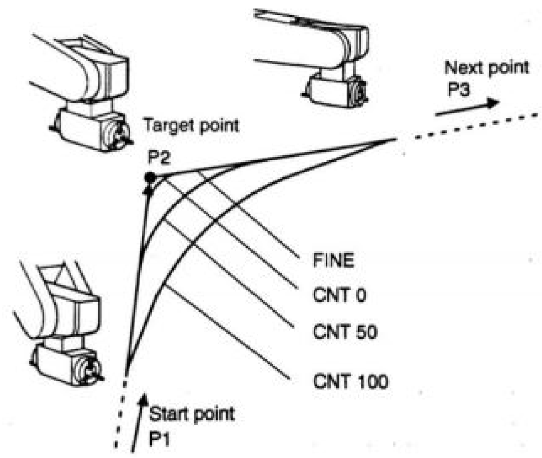


Figure 5.4: Precision of points [10]

Robot movements

The robot program is visualised in Figure 5.5 with a flow chart that uses the following legend:

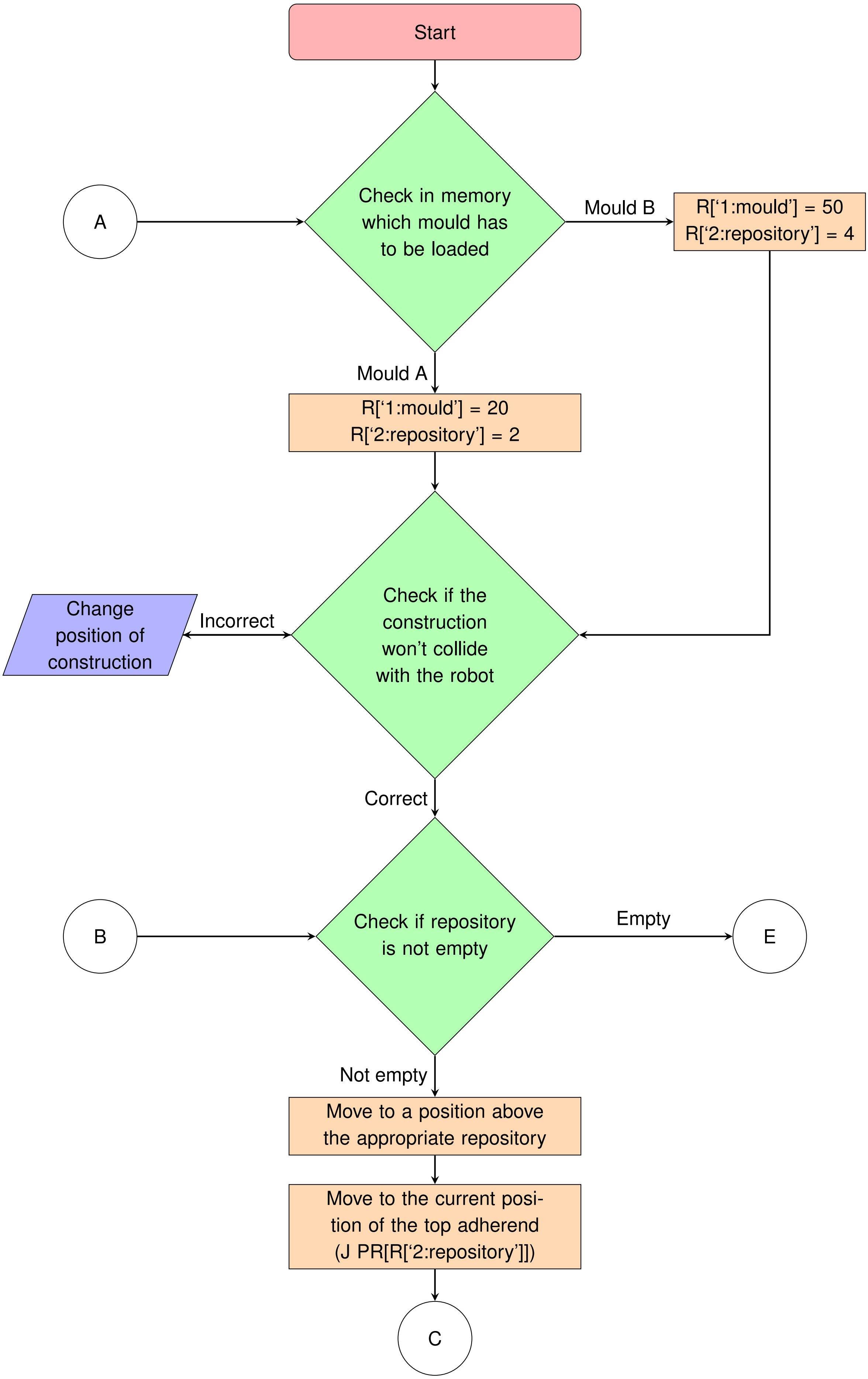
- Green rhombus boxes are used to define decisions.
- Blue trapeziums denote an input that has been sent or an output that has been received from the connected devices (i.e. the adhesive dispensing machine or the Raspberry Pi).
- Orange rectangles are responsible for robot movements or changes in variables in the robot its memory.
- White circles are used to denote pointers to where a program jumps. These pointers are also used at the beginning and the ending of a page to indicate their progress on the following page.

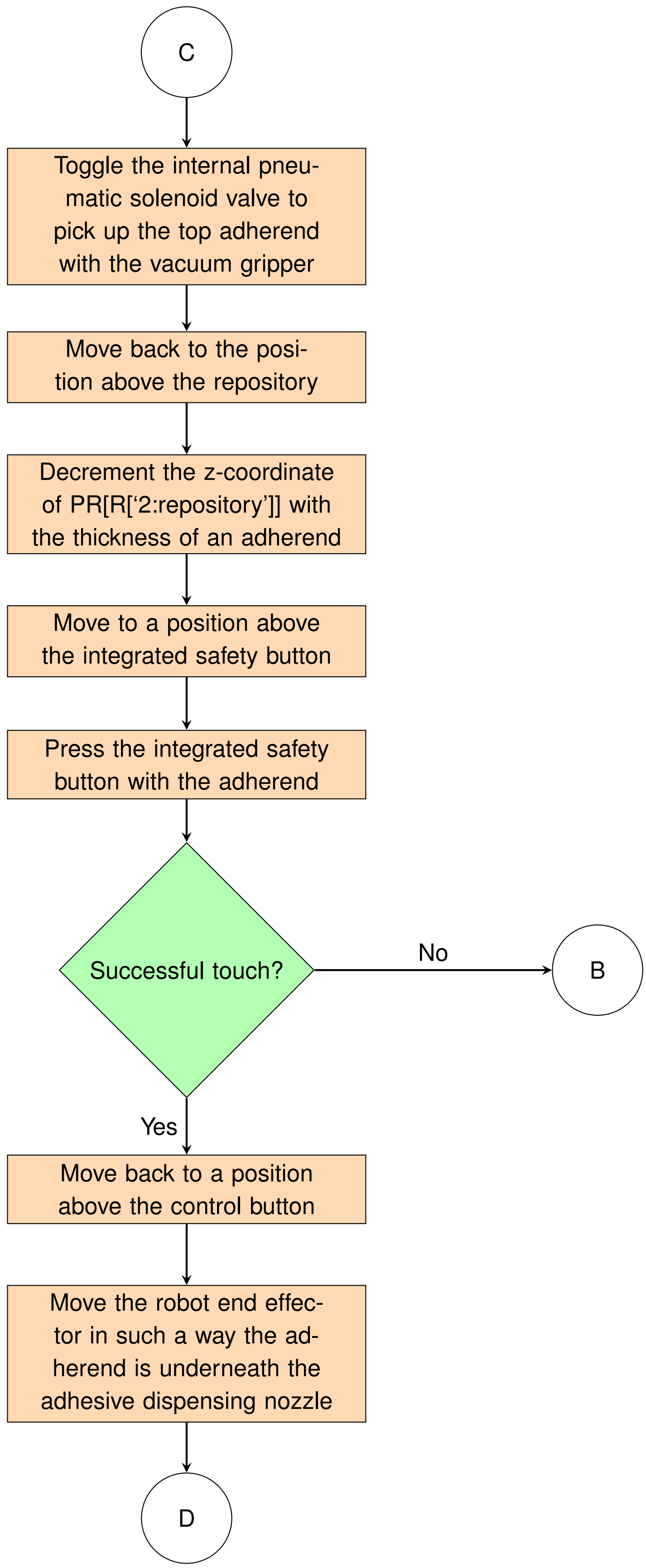
The integer register 'R['2:repository']' stores which repository is being unloaded. The corresponding position register its z-coordinate gets decrement by the thickness of an adherend every cycle to indicate the new top adherend.

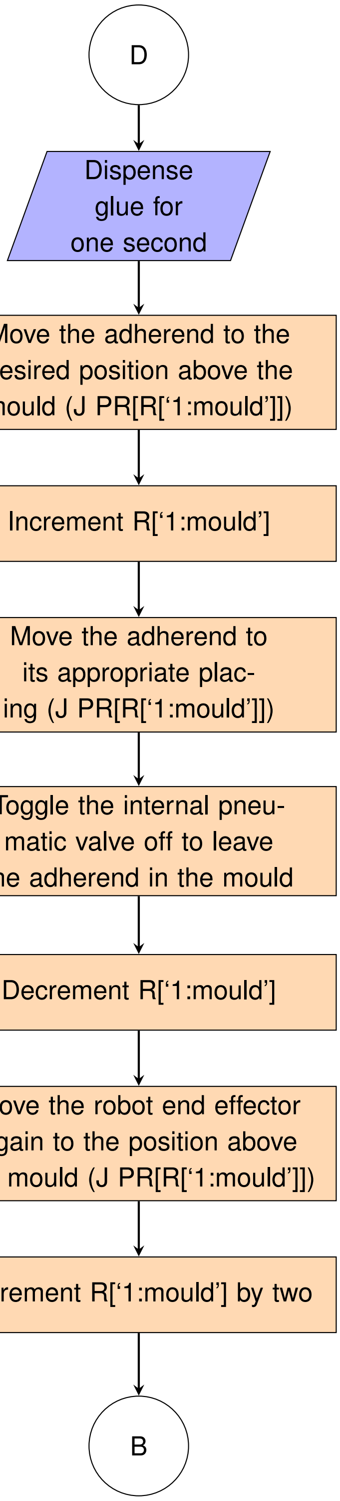
Besides, it is important to note that the position registers 20 to 31 and 50 to 61 are used to denote positions above certain placings in the mould (even registers) and positions corresponding to the certain placings (odd registers). Hence, a similar approach as the example from Figure 5.3 can be used, which arises in the flowchart on page 45.

Additionally, before and after the robot moves to a specific point, it first rounds a point above the specific point to avoid that an adherend's edge touches the robot table. This could happen since the robot rotates its axes independently from each other, which translates in an arrival of the adherend at an angle.

The last element to mention is the fact that the detected condition of a sample can be either acceptable (store sample) or unacceptable (refuse sample).


Start
A
Check in memory which mould has to be loaded
Mould B
R[‘1:mould’] = 50
R[‘2:repository’] = 4
Mould A
R[‘1:mould’] = 20
R[‘2:repository’] = 2
Change position of construction
Incorrect
Check if the construction won’t collide with the robot
Correct
B
Check if repository is not empty
Empty
E
Not empty
Move to a position above the appropriate repository
Move to the current position of the top adherend (J PR[R[‘2:repository’]])
C


C
Toggle the internal pneumatic solenoid valve to pick up the top adherend with the vacuum gripper
Move back to the position above the repository
Decrement the z-coordinate of PR[R['2:repository']] with the thickness of an adherend
Move to a position above the integrated safety button
Press the integrated safety button with the adherend
Successful touch?
No
B
Yes
Move back to a position above the control button
Move the robot end effector in such a way the adherend is underneath the adhesive dispensing nozzle
D


D
Dispense glue for one second
Move the adherend to the desired position above the mould (J PR[R['1:mould']])
Increment R['1:mould']
Move the adherend to its appropriate placing (J PR[R['1:mould']])
Toggle the internal pneumatic valve off to leave the adherend in the mould
Decrement R['1:mould']
Move the robot end effector again to the position above the mould (J PR[R['1:mould']])
Increment R['1:mould'] by two
B

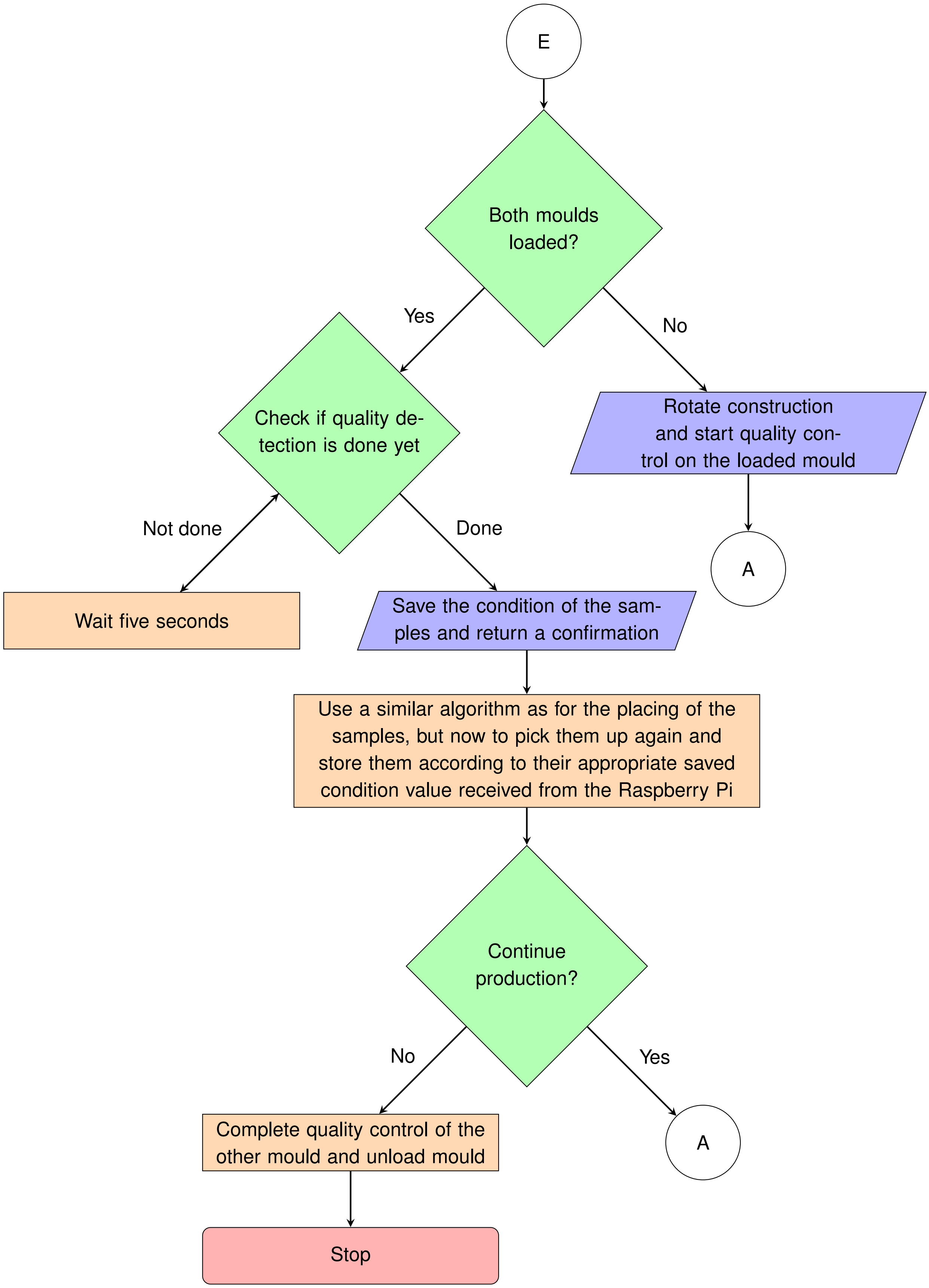


Figure 5.5: Flowchart of robot program

5.2 Vision program

The objective of the vision program is to detect whether the distribution of the glue is uniform and if the curing has finished yet. This is made possible with the use of a Raspberry Pi, which runs a Python program that is making use of OpenCV, an open source library focusing on computer vision. The frames of the camera each undergo a chain of processes, so all samples are classified as to be accepted or to be refused. This chain of processes is often called a pipeline. A qualitative analysis of this pipeline is provided in Section 5.2.1 whereas the code itself can be found in Appendix D.

5.2.1 Pipeline

The following routine is repeated for every frame from the camera:

1. The mould gets extracted from the whole picture to behold only relevant information, which is obtained with a transformation matrix. Parallax effects due to the camera position are removed as well. This extraction of the mould is necessary since the positioning of the camera above the mould is not perfectly accurate due to eventual deviations while rotating the construction.

2. Once the mould dimensions are shown perfectly on scale, the positions of the gluing areas of the samples can be determined due to the fact that the natural coordinates from these areas can be measured on the mould itself.

3. A sample gets detected as cured once the colour of the glue in the gluing area rises above a certain threshold, keeping in mind that the colour of the glue depends on the curing condition. Moreover, a sample gets classified by the glue its uniformity.

Each of these subroutines will be further explained in the following paragraphs.

Extracting the mould

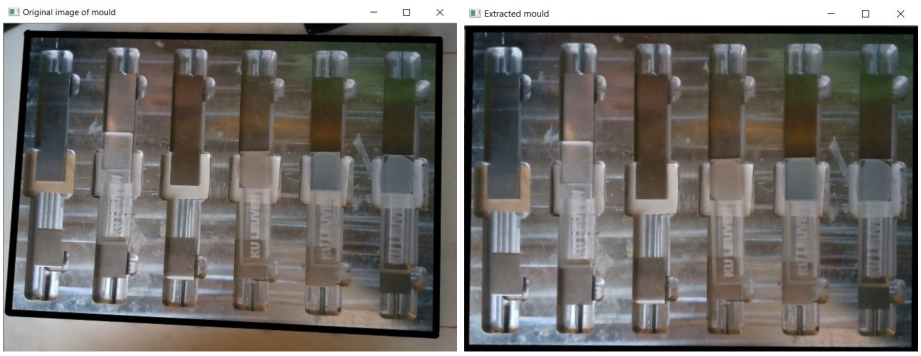
The image from the camera contains 1280 x 720 pixels, where each pixel consists of three bytes. These bytes correspond to the red, green and blue values from the RGB-model which can be combined due to additive mixing into one colour for a pixel.
The following steps explain how the mould is extracted from the image [53]:

1. The image gets transformed in grayscale, mandated for the following step. The pixels, which consists of three bytes, are transformed in pixels of one byte containing just the intensity of a pixel.

2. It is desirable to detect the edges of the mould, since the coordinates of the corners have to be determined. Thresholding is a method to create binary images, where a pixel can be either high or low. Simple thresholding changes an 8-bit pixel into binary low if its value is lower than a certain threshold and into binary high if its corresponding value is higher than a certain threshold. However, to detect edges of an object with different lighting conditions, a more sophisticated method has to be used. The method *adaptive thresholding* in OpenCV calculates various threshold values for various regions, making the method less prone to different lighting conditions.

3. The edges are converted in closed contours, which are sorted on their enclosed surface.
4. The corners of the most outer contour (i.e. the contour around the mould) are determined, along with the height and width of this contour.
5. A *perspective transformation function* relates the positions of the four corners with each other and creates a transformation matrix to transform the image with parallax effects into a scaled rectangle. Consequently, the original image gets multiplied by this transformation matrix to obtain the desired scaled image.

Unfortunately, the algorithm has some problems with the detection of the mould due to the low contrast differences between the aluminium mould and the wooden base plate, as well as bad due to lighting conditions. This could be easily resolved by painting the wooden base plate or the mould, however, this problem was only discovered in the conceptual phase of this research. Hence it has been resolved by marking the edges of the mould as can be seen in Figure 5.6a. Consequently, the algorithm successfully extracts the mould, beholding only relevant information as shown in Figure 5.6b.



(a) Original image of the mould **(b)** Extracted image of the mould

Figure 5.6: Extracting the mould

Determining the positions of the gluing areas of the samples

The exact positions of the gluing zones can be measured on the mould itself, followed by dividing this measurements to the total length and height of the mould to determine proportions, which are very similar to natural coordinates. Furthermore, a rectangle is captured with two coordinates, hence twelve natural coordinates are saved in a list that is being iterated to cut out the appropriate gluing areas. Although these areas are relatively small and rather prosaic, Figure 5.7 shows an example of such a gluing area for the sake of completeness.

Figure 5.7: Example of a gluing area

It should be noted that the positions of the gluing zones have been determined from Figure 5.6b by respectively dividing the height and length coordinate of a particular pixel by the total amount of height and length pixels. An example of the natural representation of the first gluing area has been shown in Equation 5.2.1. The upper left height pixel value equals 185 while the total height of the extracted image on scale is 438 pixels. The same reasoning applies for the upper left length proportion $(33/610)$, hence the combination of the two provides the first of the twelve natural coordinates.

$$First\ gluing\ area = [[185/438, 33/610], [231/438, 72/610]] \tag{5.2.1}$$

Curing detection

Each of the six samples should have a uniform gluing zone in combination with a maximum curing time. If therefore all the uniform samples are cured before the maximum curing time has expired yet, unloading can start earlier on. The determination of the curing condition of the samples can be derived from the colour of the glue, since this specific two-component adhesive has the property that its colour changes while curing. However, the quality of the adhesive bond in the few test samples that were available is unacceptable, hence the appropriate colour for a cured sample could not be determined. The subroutine of this particular section is therefore only explained qualitatively.

A grid of a predefined amount of intersections is laid over the gluing areas that has been defined in the previous paragraph. The specific average colour over the neighbourhood of each pixel from an intersections of the grid is determined, after which the curing condition at that particular point is derived. Since it is also possible to distinguish the colour between a point that is not glued and a point that is under curing, the uniformity of a sample can be derived as well.

5.3 Conclusion

The Fanuc TeachPendant turned out to be the most suitable programming environment for the Fanuc CR-7iA/L. By using double registers, a comprehensible robot program is obtained which should be able to produce representative samples, while using the Raspberry Pi to obtain a quality control. This quality control makes use of pipeline which extracts the mould from the image, determines the gluing areas of the samples and detects the curing condition and uniformity of a sample.

6 Discussion and conclusions

The robot program that practically has been made was able to take an adherend from the repository with its vacuum grippers, bring the adherend to the adhesive dispensing nozzle, attach glue on the adherend and push it on an aluminium plate to create a sample. However, as mentioned in Section 1.2, around the moment that testing this setup would start, the COVID-19 outbreak restricted the possibilities to test the setup. Hence, no usable samples were produced for analysis. This chapter will therefore discuss the experiences gained during the testing phase instead of objective experiments that have been conducted on the samples.

The research commenced with the objective to produce representative samples by using a robot. Moreover, to intercept random errors due to fluctuations, an additional objective became to add a quality control. Hence, the two research questions were summarized as follows:

1. Could representative samples, consisting of aluminium and plexiglass plates joined by an adhesive bond, be produced with an automated gluing process assisted by a robot?
2. Could the uniformity and the curing condition of an adhesive bond be determined with a camera, by using an adhesive which colour is curing-dependent?

The findings and limitations concerning the research questions are enlisted in respectively Section 6.1 and Section 6.2.

6.1 Findings and limitations concerning the possibility to produce representative samples with an automated gluing process

The first objective of this research was to link the adhesive dispensing machine with the robot. The two mandatory linkages were the back and forth connection from the emergency buttons since it is prohibited that one of the machines stays producing while the other one is malfunctioning. Consequently, it was desired to let the robot send extrusion requests to the adhesive dispensing machine. These three connections were successfully achieved, laying a foundation for further work.

Consequently, before starting with programming the robot, it was desired to hold test-samples with a gripper to have an idea of the gripper's abilities. However, the ultimate samples were still under consideration at the time that the vacuum gripper had to be chosen. Keeping in mind the drawbacks and benefits from the available vacuum grippers (Table 3.1), the Schmalz Vacuum End Effector has been chosen as the best fitting vacuum gripper with the current information.

In hindsight, the choice for the Schmalz VEE was by far the best choice from the four available vacuum grippers. The relatively small samples could have been taken with the Schmalz FXCB (Figure 3.9a) since this gripper does have an intelligent vacuum area, though the samples had to be placed in placings in the mould which were relatively tight. Therefore, the Schmalz FXCB would have caused problems. The other grippers do not have such an intelligent vacuum gripper, hence air would be drawn from the places next to the sample, consequently losing its vacuum power.

Once the vacuum gripper had been chosen and the desired linkages has been made, the programming of the robot could start. A choice had to be made which programming environment would be used, keeping in mind the second research question. There were also ideas in the beginning of this research to feedback the robot so that potential quality issues could be rectified. A lot of time had therefore been spent on the investigation of these environments, but it turned out that this particular robot started to work very slowly when receiving feedback instructions. Hence, the idea to rectify the samples was discarded and the Fanuc Teachpendant was used for future programming.

The robot should, in this first programming stage, be able to pick up samples from the repository and place it accurately in the mould. Despite the fact that this robot should have a high accuracy and a repeatability up to 0.01 mm [39], there were some concerns about the fixation of the robot on the robot table, since there has been some troubles in previous applications. This concern was reinforced by ascending deviations on the force sensor over time. However, since the robot did not make practical usage of the force sensor, the position measurement was better than expected and it turned out that the robot had the ability to achieve a high repeatability and accuracy. Hence, representative samples could be produced with this robot on condition that the adhesive dispensing machine is accurate as well.

Unfortunately, the plastic mix unit on the adhesive dispenser nozzle was not that accurate while dispensing. The end of the mix unit could randomly deflect a few centimetres at the moment of dispensing due to the sudden pressure rise. However, this limitation could have been easily resolved by placing a ring around the tip of the mixing unit which is then immobilized by connecting it to the adhesive dispensing construction.

Although the fact that the desired samples have not been made and the problem that the end of the mixing unit deflects, this setup does have the potential to produce representative samples within a few hours of modifications. In particular, it should have been possible to immobilize the tip of the mixing unit and start the production of some samples in a short amount of time, which could have proven this claim. Unfortunately it was not known that the access to the campus would be restricted that fast.

6.2 Finding and limitations concerning the quality control on the samples with the use of a camera

Although the quality of the camera was too low to mount the camera above the robot's working zone and the camera could not be completely fixed in the working zone, the camera should have the possibility to behold the mould without colliding with the robot. This has been achieved with a rotating construction (Figure 4.1) which can be balanced by counterweights. An additional restriction here was the desire to print this construction on the campus, hence the construction was broken down in three pieces that could rigidly be linked with each other.

The quality control could start once the camera had been positioned above a mould. The program made for this quality control extracts the mould from the image since the positioning of the camera is not perfectly accurate due to eventual deviations while rotating the construction. A series of steps could first detect the edges of the mould with the use of adaptive thresholding, to convert this to the corners of the mould and finally to calculate a transformation matrix which transforms the original image to an image which only beholds the extracted mould on scale. However, detecting the edges from the mould has not succeeded even though adaptive thresholding has been used, which is less prone to different lighting conditions than normal thresholding algorithms. Various possibilities have been tried to pre-process the image in a better way, but were unfortunately unsuccessful.

On the other hand, it could be shown that if the contrast differences between the aluminium mould and wooden base plate increases, the extraction algorithm succeeds. This has been proven by slightly adapting the edges of the mould, which is shown Figure 5.6. Hence, the easiest way to overcome this obstacle should be by painting the mould or the wooden base plate to increase the contrast differences, or by adapting the edges of the mould with a black adhesive tape. Consequently, the gluing areas of the samples could be determined by their natural coordinates.

The last step in this pipeline should have to detect the curing condition of the samples. This can be done since the colour of the glue should have to change while curing, hence the curing condition could be derived from the colour. Nevertheless has there only been made a few samples, where the colour differences over time are almost undetectable.

It had to be admitted that the answer on the second research question is rather non-conclusive, since the subroutine 'curing detection' is highly dependent on the amount of colour change of the glue, which had not been determined accurately. In a case where the glue does not provide colour changes over curing time, it seems almost impossible to detect in a non-destructive way whether or not the adhesive bonding is cured.

Besides, it is important to note that existing adhesive dispensing applications use vision capabilities too. Section 2.4.2 shows a study from Z. Yang et al. [35] where the gluing quality is determined by comparing the captured image with a standard image to construct a matching feature vector. The main differences between this study and the study from Z. Yang et al. is the fact that the camera in their study was fixed while the camera in the current study rotates. They could therefore directly compare each image with the standard image while in this study it was mandatory to first extract the mould, hence creating a standardized image. Z. Yang et al. also made use of a visual servo, where the robot motion path was modified with a closed loop control system, something that seemed not achievable with the robot from this study.

On the other hand, this study may also benefit from constructing a matching feature vector. Keeping in mind that the deviations of the rotating camera construction are relatively small, the matching feature vector between a frame of ideal positioning and the real frame would be small. In this case, it is known in advance with high probability where the edges of the mould should be, which would lower the search area. Therefore, the extraction algorithm would not confuse the edges of the mould with lines in the middle of the mould, which may increase the likelihood of successful extraction.

6.3 Recommendations for further research

Mixing unit Logically, it is advised to fix the tip of the mixing unit before further investigations are undertaken since these deflections cause high inaccuracies.

Fanuc TeachPendant The Fanuc TeachPendant is a useful way of programming pick and place applications but, however, has no integrated possibility to receive feedback from a Raspberry Pi or something similar and correct robot movements hereupon. It is therefore recommended that an other programming method is used. Such other programming environments mostly support for example Python scripts which are loaded in these environments and takes therefore away connections that have to be made between the robot controller and the device where the script runs for providing vision capabilities.

Mould extraction It is advised to increase the contrast differences between the mould and the wooden base plate. Additionally, it may be useful to improve the lighting conditions by shielding sunlight from the window. Alternatively, it may be useful to improve the mould extraction algorithm with for example a matching feature vector, which could increase the likelihood of successful extraction.

Curing detection Finally, it is strongly advised to investigate the two components of the adhesive dispensing machine to find out if there are conditions at which the colour differences through curing are more detectable. This may possibly be achieved by changing the dosage of product A relative to B, changing the pressure on the storage containers and many more.

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A

Corresponding wiring circuits of the adhesive dispensing machine

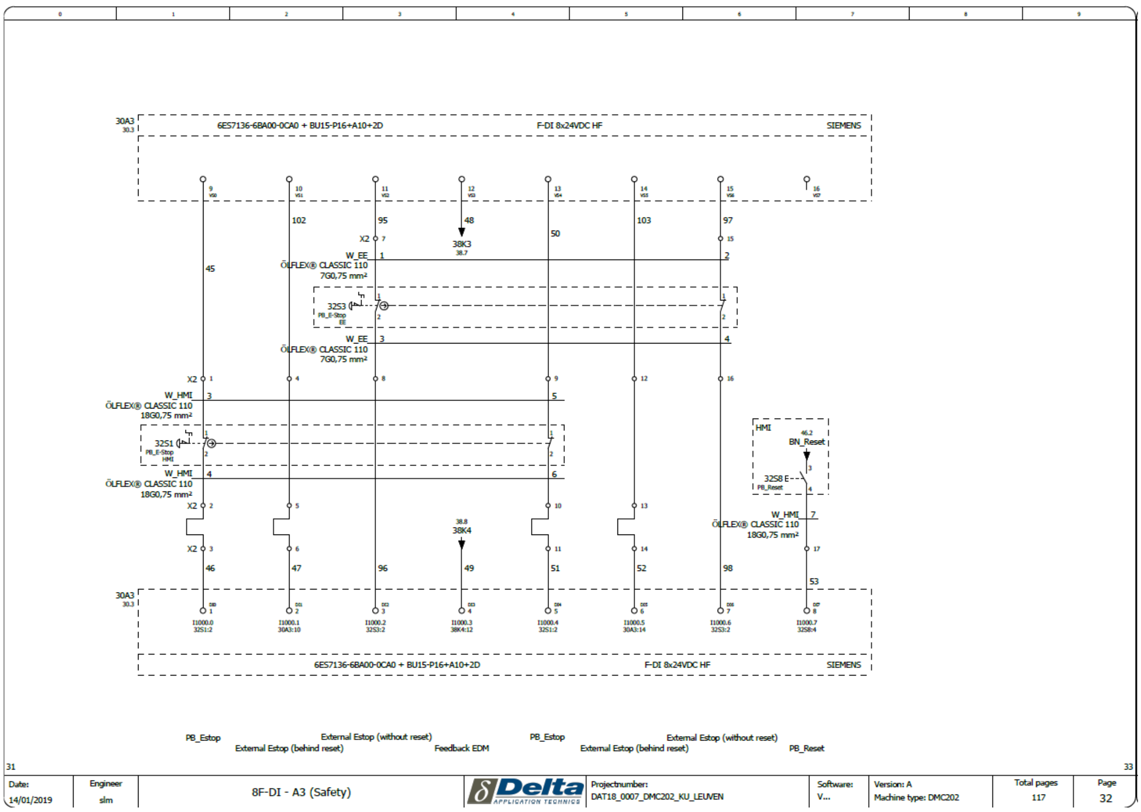

Figure A.1: Adhesive dispensing machine — PLC A3 (Safety) [11]

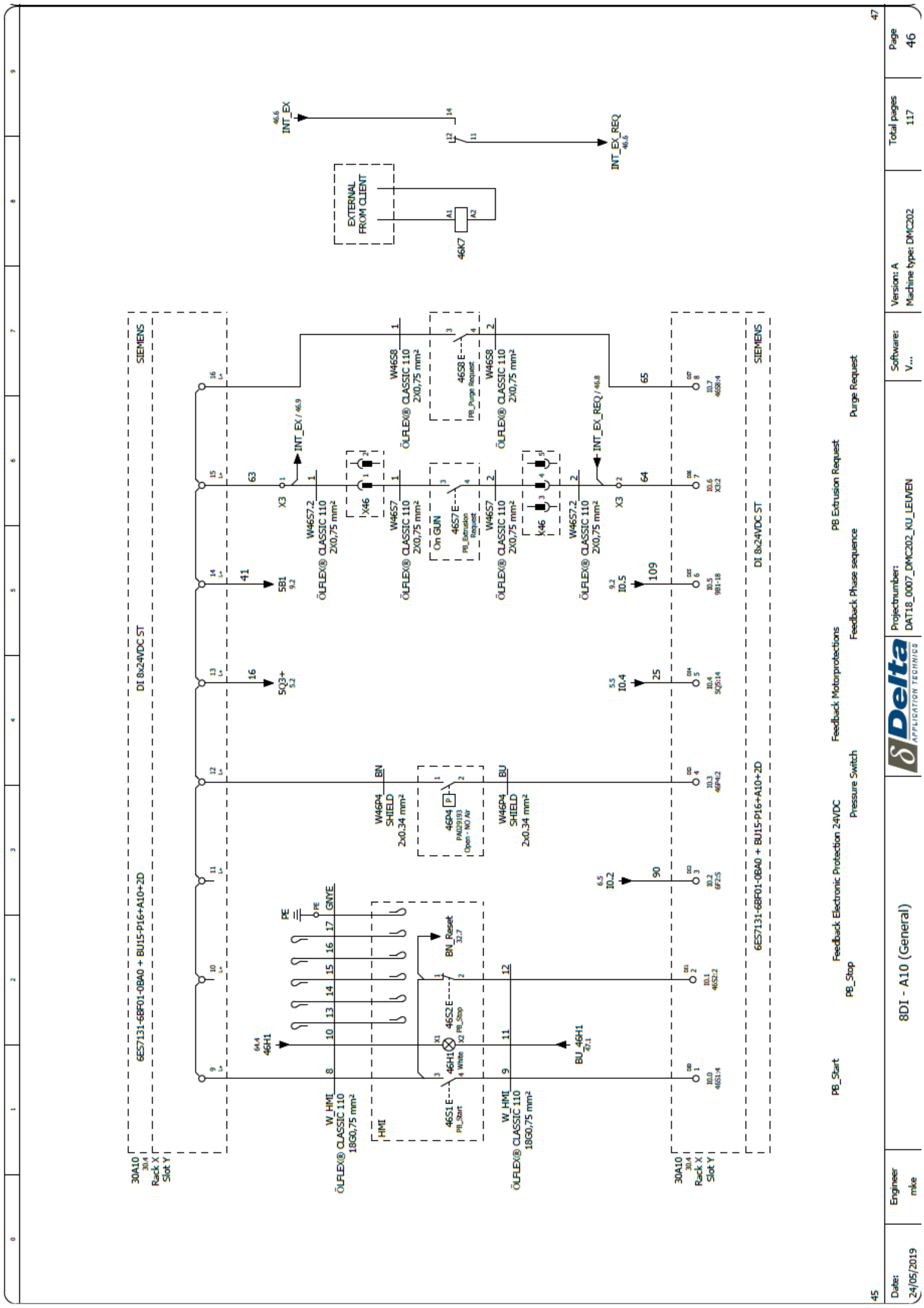

Figure A.2: Adhesive dispensing machine — PLC A10 (General) [11]

B
Fanuc I/O link

In addition to the connections from Table B.1, it is important to note that port 18 of Figure B.1 is connected to the ground of the adhesive dispensing machine, as shown in Figure 3.13 and Figure 3.15 via connector 1, as well as to the ground of the Raspberry Pi. Furthermore, port 32 and port 50 from Figure B.1 are connected with each other since the I/O link requires supply voltage.

Peripheral device A3

01	DI121			33	DO121
02	DI122	19		34	DO122
03	DI123	20		35	DO123
04	DI124	21		36	DO124
05	DI125	22		37	DO125
06	DI126	23		38	DO126
07	DI127	24		39	DO127
08	DI128	25		40	DO128
09	DI129	26		41	
10	DI130	27		42	
11		28		43	
12		29	0V	44	
13		30	0V	45	
14		31	DOSRC3	46	
15		32	DOSRC3	47	
16				48	
17	0V			49	+24F
18	0V			50	+24F

Figure B.1: Fanuc I/O link [9]

I/O Fanuc	Usage
DO121	Extrusion request
DO122-123	Desired position of rotating construction
DO124	Acknowledgement (ACK)
DI121	Integrated safety button
DI122-127	Condition of samples
DI128-129	Actual position of rotating construction

Table B.1: Connections of the Fanuc I/O link

C
Raspberry Pi I/O link

Table C.1 proposes a configuration to connect the Raspberry Pi with the robot. However, the connection between the Raspberry Pi and the robot requires the usage of optocouplers, as elaborated in Section 4.3. Since this connection is only studied on a conceptual level, the exact design of the coupling is beyond the scope of this research.

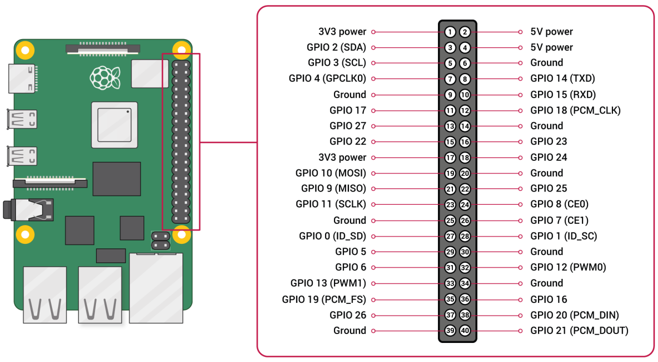

Figure C.1: Raspberry Pi I/O link [12]

I/O Raspberry Pi	Usage
GPIO 4	Receive acknowledgement (ACK)
GPIO 20-21	Send actual position of construction
GPIO 12-13	Receive desired position of construction
GPIO 22-27	Send condition of samples

Table C.1: Connections of the Raspberry Pi I/O link

In addition to the connections from Table C.1, it must be noted that port 39 (ground) is connected to the ground of the robot.

D
Vision program

```python
import numpy as np
import cv2


def detect_mould(image):
    """Detect the corners of the mould and extract the mould from the original image.
    """
    original = image.copy()
    image = cv2.cvtColor(image, cv2.COLOR_BGR2GRAY)
    blurry = cv2.adaptiveThreshold(image.astype(np.uint8), 255, cv2.ADAPTIVE_THRESH_MEAN_C, cv2.THRESH_BINARY, 11, 3)
    contours, _ = cv2.findContours(blurry, cv2.RETR_TREE, cv2.CHAIN_APPROX_SIMPLE)
    contours = sorted(contours, key = cv2.contourArea, reverse = True)
    contour = contours[1] # contours[0] beholds the whole picture, contours[1] beholds the mould.

    margin = 0.01 * cv2.arcLength(contour, True)
    non_sorted_corners = cv2.approxPolyDP(contour, margin, True)

    if len(non_sorted_corners) == 4: # Rectangle
        transformed_image = transform_image_by_coordinates(original, non_sorted_corners.reshape(4, 2)) # Reshape desirable to work with a more convenient list.
    return transformed_image

def transform_image_by_coordinates(original, non_sorted_corners):
    """Transform the original image to the image that only beholds the mould starting from the unsorted corners of the mould."""
    four_corners = organize_points(non_sorted_corners)

    length_upper = np.sqrt(((four_corners[1][0] - four_corners[0][0]) ** 2) + ((four_corners[1][1] - four_corners[0][1]) ** 2)) # Calculate the length of the upper edge of the mould.
    length_lower = np.sqrt(((four_corners[3][0] - four_corners[2][0]) ** 2) + ((four_corners[3][1] - four_corners[2][1]) ** 2)) # Calculate the length of the lower edge of the mould
```

```python
    maximum_length = max(int(length_upper), int(length_lower))

    width_left = np.sqrt(((four_corners[2][0] - four_corners[0][0]) ** 2) + ((four_corners[2][1] - four_corners[0][1]) ** 2)) # Calculate the width of the left edge of the mould.
    width_right = np.sqrt(((four_corners[3][0] - four_corners[1][0]) ** 2) + ((four_corners[3][1] - four_corners[1][1]) ** 2)) # Calculate the width of the right edge of the mould.
    maximum_width = max(int(width_left), int(width_right))

    scaled_coordinates = np.array([[0, 0], [maximum_length, 0],[0, maximum_width],[maximum_length, maximum_width]], dtype = 'float32') # Coordinates of corners in new image.
    perspective_transform_matrix = cv2.getPerspectiveTransform(four_corners, scaled_coordinates)
    transformed_image = cv2.warpPerspective(original, perspective_transform_matrix, (maximum_length, maximum_width))
    return transformed_image

def organize_points(coordinates):
    """Sort the points that way that the upper left coordinate is the first value of the list, the upper right coordinate is the second value, the lower left coordinate is the third value and the lower right coordinate is the fourth value of the list."""
    four_corners = np.zeros((4, 2), dtype = 'float32')

    sum_over_coordinates = coordinates.sum(axis = 1) # Calculate the sum of the x and y coordinate. The maximum yields the lower right corner, while the minimum yields the upper left corner.
    four_corners[0] = coordinates[np.argmin(sum_over_coordinates)] # Upper left
    four_corners[3] = coordinates[np.argmax(sum_over_coordinates)] # Lower right

    subract_over_coordinates = np.diff(coordinates, axis = 1) # Subtract the y coordinate of the x coordinate. This minimum value yields the upper right corner, while the maximum value yields the lower left corner.
    four_corners[1] = coordinates[np.argmin(subract_over_coordinates)] # Upper right
    four_corners[2] = coordinates[np.argmax(subract_over_coordinates)] # Lower left
    return four_corners

def extract_six_gluing_areas(image):
    """The natural coordinates are determined with the use of an image on scale. This is a valid method since all the input images will have the same scale."""
    natural_coordinates = [[[185/438, 33/610], [231/438, 72/610]], [[180/438, 133/610], [224/438, 172/610]], [[183/438, 233/610], [230/438, 270/610]], [[181/438, 330/610], [232/438, 373/610]], [[176/438, 433/610], [229/438, 471/610]], [[178/438, 531/610], [234/438, 571/610]]]
    size_y = len(image)
    size_x = len(image[0])

    for coor in natural_coordinates:
        [[natural_y_upper_left, natural_x_upper_left], [natural_y_lower_right, natural_x_lower_right]] = coor
        area_image = image[int(natural_y_upper_left * size_y):int(natural_y_lower_right * size_y), int(natural_x_upper_left * size_x):int(natural_x_lower_right * size_x)]
        yield area_image
```

```
if __name__ == '__main__':
    frame = cv2.imread('frame.jpg')
    transformed_image = detect_mould(frame)
    cv2.imshow('Extracted mould', transformed_image)
    gluing_areas = extract_six_gluing_areas(transformed_image)
    keyCode = cv2.waitKey(0)
    for area in gluing_areas:
        cv2.imshow('Extracted gluing area', area)
        keyCode = cv2.waitKey(0)
```

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