Master Thesis

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Development of an End-Effector for an Industrial Robot for the automated Integration of threaded Inserts into a hybrid additive Manufacturing Process

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Development of an End Effector for an Industrial Robot for the Automated Integration of Threaded Inserts into a Hybrid Additive Manufacturing Process

Entwicklung eines Endeffektors für einen Industrieroboter zur automatisierten Integration von Gewindeinserts in einen hybriden additiven Fertigungsprozess

In the scope of the project "Innovationscampus Mobilität der Zukunft", a hybrid Fused Filament Fabrication (FFF) process has been developed. The goal of the project is to achieve a fully automated manufacturing process for a sensor circuit. The system currently consists of a 3D printer with four print heads and an integrated milling tool, as well as an industrial robot. Function integrated parts are produced by combining non conducting filament for the housing and conducting filament for the trace, which can be post processed with the milling tool. The industrial robot is used for automated integration of inserts into the printing process. Currently only small circuits boards can be integrated automatically. The goal of the thesis is, to add a robotic effector to the system that is capable of automatically integrating threaded inserts into the process.

In previous work was determined that automated integration of threaded inserts would contribute to the functionality of the parts and to the degree of automatization of the total process. Currently threaded inserts are added to the process manually. Threaded inserts are used to combine the printed parts with other components, or to improve the contacting between conducting filament and integrated circuit boards by pressing them together with a bolt. They are also used to fasten plugs on the housing that connect the control electronics.

In an initial literature research, the state of the art regarding existing hybrid production systems will be described. Processes that can be used to produce function-integrated components will also be investigated. Furthermore, manual and automated processes for the integration of threaded inserts into components produced with FFF will be discussed. Based on this research, the end effector shall be developed and designed according to VDI 2221. The result is to be produced, assembled and put into operation. Finally, the functionality of the design will be validated.

Internal thesis-number:	MAP 1547
Date of issue:	2022-01-28
Last submission:	2022-07-28
Guidance:	Michael Baranowski, M.Sc.

Karlsruhe, 2022-01-28

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Karlsruhe, 26.08.2022

Lennart von Deyn

Abstract

In this thesis, a novel approach to automatically install threaded inserts into additive manufactured parts is developed and validated. Such an approach is highly relevant in the context of process automation and production of function-integrated parts. Automated production in combination with additive manufacturing has the potential for resource and energy-efficient production. This is becoming an increasingly important factor during decision making, due to climate change. Furthermore, additive manufacturing can support the development of climate-friendly solutions across all fields of application, as it enables quickly adaptable designs and flexible production methods. In addition, new design approaches to produce function-integrated components are becoming available. Integrating mechanical and electrical functional components during manufacturing makes it possible to realise an efficient and cost-effective integration procedure. The Fused Filament Fabrication (FFF) process can be used for this purpose, as it allows easy automation and expandability compared to other additive processes, plus a wide variety of materials can be processed.

Initial literature research on the state of the art shows, that currently no process has been described, that combines the FFF process with a subtractive process and conductive filament. The 4K-FFF unit, the subject of this thesis, offers a unique approach to the automated production of function-integrated components. The system consists of a multi-material FFF printer with a milling and handling module. Manufacturing inaccuracies resulting from the FFF process can be compensated by the milling module. An industrial robot on the handling module is used to add functional components to the process. This setup enables the fully automated production of function-integrated components. For fastening and contacting the function-integrated components, threaded inserts are used, which have to be installed manually due to a lack of a suitable alternative. Literature research shows that there are no methods for the automated installation of threaded inserts into individual components, which are common in FFF.

This shortcoming is addressed in this thesis. A new end-effector for the industrial robot is developed, which can grip, heat and install threaded inserts into a component. In addition, a quick-change system is established. Both expansions further increase the degree of automation of the 4K-FFF unit. A parameter optimisation procedure is carried out to determine the ideal operating parameters for the new end-effector. The functionality of the development and the quick-change system is validated by the production of demonstrator components.

Contents

Symbols and Abbreviations

Symbol	Unit	Description
Latin Symbols		
a	$\mathrm{m\,s^{-2}}$	Acceleration
g	$\mathrm{m\,s^{-2}}$	Gravitational constant
m	kg	Mass
A	°	Rotation around Z-Axis
B	°	Rotation around Y-Axis
C	°	Rotation around X-Axis
F_C	N	Contact force
F_{FC}	N	Frictional contact force
F_F	N	Frictional force
F_N	N	Normal force
G	N	Gravitational force
JX	$\mathrm{kg\,m^2}$	Mass inertia around the X-axis of the main axis system
JY	$\mathrm{kg\,m^2}$	Mass inertia around the Y-axis of the main axis system
JZ	$\mathrm{kg\,m^2}$	Mass inertia around the Z-axis of the main axis system
S		Security factor
Greek Symbols		
α	°	Angle
μ		Friction coefficient
Abbreviations		
ABS		Acrylonitrile Butadiene Styrene
CAD		Computer AidedDdesign
CIRP		International Academy for Production Engineering
CNC		Computerized Numerical Control
COG		Centre of Gravity
DED		Directed Energy Deposition
DIW		Direct Ink Writing
ERW		Electric Resistance Welding
FDM		Fused Deposition Modelling
FFF		Fused Filament Fabrication
KRL		Kuka Robot Language

LIN	Linear Movement
MIA	Main Inertia Axis
MID	Mechatronic Integrated Devices
MJM	Multi Jet Modelling
NC	Numerical Control
PBF	Powder Bed Fusion
PCB	Printed Circuit Board
PLA	Polylactic Acid
PLC	Programmable Logic Controller
PTP	Point to Point
SLS	Selective Laser Sintering
TCP	Tool Centre Point
TFM	Transversal Flux Machine
Wt	Weight
Wtv	Weighted Value

1 Introduction

1.1 Motivation

Efficient manufacturing and automation enable climate-friendly production, which is increasingly becoming important as climate change and environmental protection have become central concerns for politics and society. With the recent decision to ban the registration of internal combustion engines in 2035, the EU Parliament has responded to the recommendations of climate protection experts and the demands of activists. The ban on internal combustion engines requires more efforts toward developing and optimising electric drive vehicles. As part of the "InnovationCampus – Mobilität der Zukunft (ICM) "project, research is being conducted to develop new propulsion methods for electric mobility. The topic of this thesis is associated with the field of „Additiv-subtraktive Fertigung multi-materieller sensorintegrierter Komponenten elektrischer Maschinen für die e-Mobilität am Beispiel der Transversalflussmaschine (AddiMoT)“. In this project, temperature and oscillation sensors are to be integrated into the functional components of a transversal flux machine (TFM), which will allow continuous monitoring of the operating conditions and thus the prevention of damage during the product's life cycle. The TFM is a potentially promising engine type for electromobility that will be further investigated in the project.

The process used to manufacture the sensors is a FFF process. The advantages of additive manufacturing are utilised in this procedure. Complex components can be manufactured in a decentralised manner, while the process conserves resources (Walter & Marcham (2020)). Due to the unique design of the 4K-FFF unit, which is used to produce the sensor components, function-integrated components can be manufactured. For this purpose, a combination of external components installed by an industrial robot, conductive filament and conventional filament is used. The process is already highly automated, although one sub-component must be installed manually. The degree of automation of the process is to be increased within the scope of this thesis by developing a new tool for an industrial robot, as automated processes enhance the competitiveness of a product and offer the potential to improve product quality.

1.2 Research Objectives

This thesis aims to extend the functionality of an existing additive manufacturing system. The system can print up to four filaments, including conductive filaments. Therefore, a combination of conductive and non-conductive filament can be used to produce function-integrated components. In addition, the 4K-FFF unit features an industrial robot that can insert external components into manufactured parts. The robot has already been used to insert circuit boards with sensors into the process. Threaded inserts are used for contacting and fastening the manufactured components. These currently have to be installed manually. The objective of this thesis is to design, manufacture and implement a tool for the industrial robot that is capable of picking up, transporting and installing threaded inserts automatically. For this, the challenges of how to realise the correct installation depth and the centring of the inserts have to be solved. In addition, a transport method for the inserts must be developed and a way to heat them must be provided. Since the inserts are heat-embedded, it must be ensured that components of the tool do not overheat. As part of implementing the tool into the existing system, the programming of the robot needs to be adapted and a control sequence for the developed effector needs to be established. Operational parameters are to be determined, and the overall functionality of the development is to be demonstrated by a series of experiments. The implementation of the mentioned additions to the system aims to increase the degree of automation of the 4K-FFF unit.

1.3 Structure of the Thesis

The structure of the scientific work is shown in figure 1.1. At first, the project's motivation is discussed, and a research objective is defined. In chapter 2, the fundamental principles for understanding the thesis are examined. First, manufacturing processes in general and later additive manufacturing processes focusing on FFF are explained. Furthermore, the principles of operation and key figures of industrial robots are discussed. Finally, the function of the TFM is briefly discussed, and the VDI 2221, according to which the development process is carried out, is described.

Chapter 3 presents the state of the art in research and technology regarding advanced manufacturing processes. Hybrid processes and function integrating processes are discussed. Furthermore, the existing manual and automated methods for integrating threaded inserts into plastic components and the characteristics of threaded inserts are described. Finally, the status of the 4K-FFF unit is presented in detail, and a potential for improvement is derived from the state of the art.

The fourth chapter describes the individual approach to developing an end-effector. The development process is described in detail following the mandatory steps of VDI2221. In addition, the selection of a quick-change system required for the 4K-FFF unit is shown.

Results of the development process are described in chapter 5. At first, the implementation of the quick change system is shown, followed by the integration of the newly developed end-effector in hardware and software. The system's functionality is evaluated in an experimental trial, and operation parameters are determined. Furthermore, the process chain of the automated installation is explained, and the communication between the programmable logic controller (PLC) and the robot is described. Finally, demonstrator components are manufactured to validate, that the quick-change system and the newly developed effector can be used to install different types of inserts into parts.

In the evaluation in chapter 6, the results from chapter five are discussed with a focus on the fulfilment of requirements for the development of the end effector. For the quick change system the fulfilment of requirements is analysed in the same way. Lastly, the demonstrator parts and the added value of the newly introduced components are discussed.

Chapter 7 provides a summary of the thesis and an outlook for possible further improvements, that can be established at the 4K-FFF unit.

Figure 1.1: Structure of the thesis

2 Basic Principles

The first part of this chapter covers the fundamentals of additive manufacturing and a short overview on conventional manufacturing. These fundamentals are needed in the production procedures of function-integrated parts. Later industrial robots will be described, which are used to implement external components into function-integrated parts. Lastly, the VDI directive 2221 is explained, which is a guideline that offers a defined procedure with objective evaluation criteria for developing technical products and systems.

2.1 Manufacturing Technologies

The first part of this chapter gives a short overview of conventional manufacturing and its advantages and disadvantages, as subtractive manufacturing is used in the 4K-FFF unit. This is followed by a general insight on the basics of additive manufacturing, its process steps and types of different additive manufacturing technologies. Extrusion based machines are one of these technologies. They will be described in a separate section, as they are most significant for this thesis.

2.1.1 Conventional Manufacturing

Types of conventional manufacturing include subtractive manufacturing, casting, and forming technologies. Computerised numerical control (CNC) machines can produce parts directly from Computer aided design (CAD) data by subtractive manufacturing (Gibson et al. (2021)). Subtractive manufacturing comprises all manufacturing processes in which the cohesion of the material particles is locally eliminated, and the volume of the workpiece is thereby reduced (Förster & Förster (2018)). Machining with geometrically defined and undefined cutting edges counts into the category of subtractive manufacturing. The most relevant processes for the industry are turning, drilling and milling (Fritz & Schulze (2015)). The disadvantages of subtractive manufacturing are material consumption and waste production. Advantages are high manufacturing accuracy and high reproducibility (Awiszus et al. (2012)).

2.1.2 Additive Manufacturing

Additive processes can be used to manufacture components from solid or liquid state. The generative manufacturing processes do not separate a workpiece volume to obtain the final shape but build up the entire component volume layer by layer. It is necessary to break down the three-dimensional component into many two-dimensional layers to do this. Modern manufacturing systems generate the whole part from these two-dimensional layers (Förster & Förster (2018)).

The additive manufacturing procedure may be divided in eight steps, as proposed by Gibson et al. (2021). In the first step, the concept needs to be developed and implemented in CAD Software. A sample CAD model can be seen on the left in figure 2.1. To make the design processable for further applications, the CAD file needs to be converted to an STL file in the second step. The STL file can then be checked for errors. The STL file is converted into a readable form for the additive manufacturing machine in a third step. This is done by slicing the part into 2D planes. In this step, it is possible to plan support structures or scale the STL model to counteract shrinking. Support structures are intended to enable the production of freestanding structures, overhangs or disconnected features. The support is removed after the completion of the part. The sample CAD Model divided into 2D planes can be seen in the middle of figure 2.1. The last part of step three is the data transfer to the additive manufacturing machine. Step four is the setup of the manufacturing machine. Build parameters like print speed or temperature are adjusted. Furthermore, physical preparation can be necessary. This includes the material supply, levelling the build plate or cleaning the machine. After the preparations are finished, the build process can start in step five. The procedure can be seen on the right in figure 2.1. The part is built layer by layer until it is completed. In the sixth step, the part is removed from the build platform. The post-processing takes place in step seven, where the part is cleaned and sometimes processed with procedures like polishing or machining. Furthermore, the removal of any existing support structures takes place in this step. The last step is the usage of the part.

Additive manufacturing processes can be divided into seven categories. The most important of these categories will be explained in the following, referring to DIN Deutsches Institut für Normung (2016) and Gibson et al. (2021).

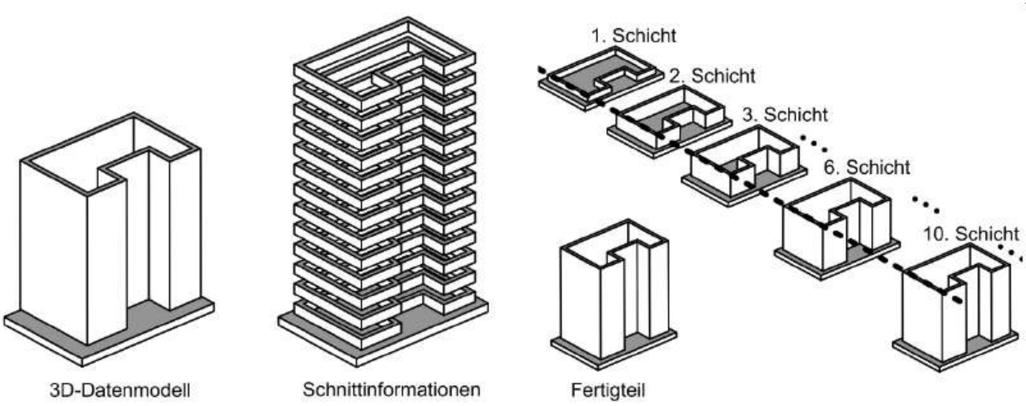


Figure 2.1: Additive manufacturing principle (Awiszus et al. (2012))

2.1.2.1 Material Jetting

Material jetting, described in figure 2.2, uses liquid photopolymer or molten wax as material. A dispensing device (2) deposits the material droplet by droplet on the build platform (5). The bonding mechanism can be by a chemical reaction or by solidification. The building platform is moved after each layer. Support structures (4) must be removed in post-processing. Post-curing by exposure to radiation may also be necessary. This procedure is used in multi-jet modelling (MJM).

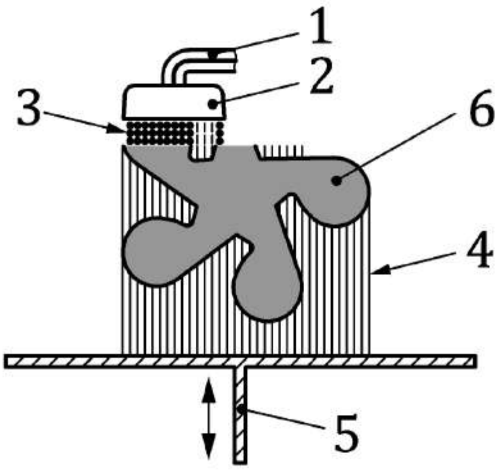


Figure 2.2: Material jetting (DIN Deutsches Institut für Normung (2016))

2.1.2.2 Directed Energy Deposition

Directed energy deposition (DED) uses the focused thermal energy of a laser, electron beam or plasma arc (2) to melt materials and bond them together while solidifying. To process can be seen in figure 2.3. The material is fed in the form of a wire (5) or a powder (1). The process is similar to material extrusion, explained in chapter 2.1.3, but with higher energy input. Due to this, materials with a significantly higher melting point can be processed. Post-processing processes are milling, polishing or heat treatment. One application of this principle is Electric Resistance Welding (ERW).

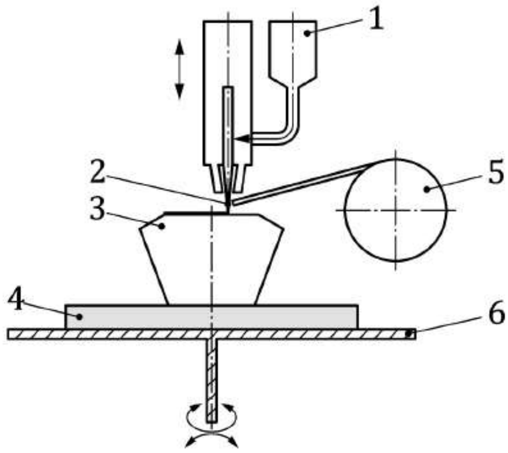


Figure 2.3: Directed energy deposition (DIN Deutsches Institut für Normung (2016))

2.1.3 Material Extrusion

Figure 2.4 illustrates the process of material extrusion. A semi-liquid material is fed from a moving nozzle (3) onto a print bed. As the material cools, it solidifies and forms a hard layer. The part (5) is built layer by layer. The connection to underlying layers results from a thermal reaction: the applied molten filament also melts the existing layer and thus bonds to the component. After a layer has been completed, the build platform (2) is lowered by one layer height. Support structures (1) may be required, which need to be removed in post-processing. Many materials can be used for this method, with thermoplastics as the most common, but uncommon materials like chocolate or clay can also be handled. The material is present in the form of a wire called filament (4). Material extrusion is commonly used in consumer-grade 3D printers (Fry, Richardson & Boyle (2016)).

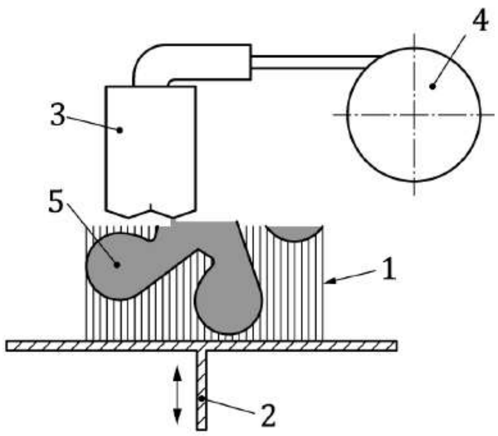


Figure 2.4: Material extrusion (DIN Deutsches Institut für Normung (2016))

FFF belongs to the group of extrusion-based machines. The procedure is also referred to as Fused Deposition Modelling (FDM), which can be used synonymously. As this is a trademarked term, FFF will be used in this thesis. In the following, types of FFF machines and major process parameters are explained in detail, referring to Dave & Davim (2021). In general, four types of FFF printers are available. The first type uses a Cartesian coordinate system. Therefore the build volume is a rectangular prism. The print head is moved relative to the build platform in the X, Y and Z axis. This can be accomplished by moving the print head or the build platform.Typical setups for Cartesian 3D printers are movable print heads in the X and Y direction with print beds moving in the Z direction. This is used in the Ultimaker 2, which manufactured test parts for the preliminary investigation. Another concept is a movable print head in the X and Z direction with a print bed movable in the Y direction, used by Prusa printers. The concept used in the 4K-FFF unit is a movable print head in X, Y and Z directions with a stationary print bed. Another type of FFF 3D printer is the delta-type model. These kinds of printers have three arms linked to vertical rails. These arms support the print head in a triangular arrangement. With a coordinated movement of the rails, the position of the print head can be adjusted. The build platform stays stationary. The build volume is nearly cylindrical. Compared to Cartesian printers, delta configurations are faster and cheaper but lack accuracy. Polar FFF printers use a circular build platform that can rotate and move laterally. The print head is movable in the Z direction. A polar coordinate system defines the print and leads to a cylindrical build volume. The last type of FFF printer is a robotic arm FFF printer. A print head is attached to a robotic arm. This setup is more expensive than the others, but it offers the opportunity for larger build volumes.

2.1.3.1 Process Parameters

Many parameters influence the quality of the end product. The most relevant are explained in detail. The extrusion temperature is the target temperature of the hot end. It defines the viscosity of the molten material that is coming out of the nozzle. Higher temperatures cause low viscosity. A material with lower viscosity flows more easily and needs less pressure to extrude. Excessive temperatures can cause degradation of the material.
The nozzle diameter is the internal diameter of the opening of the nozzle. Nozzles with larger diameters extrude more material than nozzles with smaller ones.
The layer thickness equals the travel of the print head or build plate in Z direction per layer. Typical values range from 0.05 mm to 0.4 mm. A layer height of 0.25 to 0.8 times the nozzle diameter is recommended. The smallest possible step in Z direction is defined as the vertical resolution. Printing resolution is the smallest printable detail in X and Y direction. The layer thickness has an impact on surface quality and print time. Lower values lead to better surface finish and reduced staircase effect at the cost of longer printing time. Furthermore, the quality is generally increased, as gaps and voids can be reduced. Smaller layer heights also lead to better tensile strength.
Another parameter is the infill pattern. FFF parts are typically not fully solid to save material and build time. A porous internal structure called infill is used. The infill has an impact on strength, flexibility and print time. A distinction is made between 2D and 3D patterns.
Print speed is defined as the velocity of the print head in the X-Y plane. Higher values reduce production time, but lower values lead to higher quality. The maximum speed is limited by the maximum flow rate of the nozzle, which is influenced by the nozzle diameter.
The temperature of the build platform influences the adhesion of the first layer. Therefore most build platforms are heated. Values right above the glass transition temperature are recommended.

2.1.3.2 Materials

The most common materials for FFF applications are thermoplastics. The material is stored in the form of a wire, called filament. Typical diameters are 1.75 mm or 2.85 mm. A large variety of materials is available for 3D printing. The chosen materials influence the part's properties, behaviour and process parameters (Dave & Davim (2021)). Polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) are popular materials. With the rising popularity of FFF, multiple materials for specialised applications have been developed, like water-soluble filament that is particularly suitable for support structures that are difficult to remove, conductive filament for electrical connections or flexible material (Gibson et al. (2021)).

2.1.3.3 Hotend

The hotend is the part of the printer that heats, melts and extrudes material. This device has the purpose to provide consistent temperature. It is also designed to prevent heat creep into parts of the printer that should not heat up. Figure 2.5 shows the components of a hotend. The nozzle is the part where the material exits the hotend.

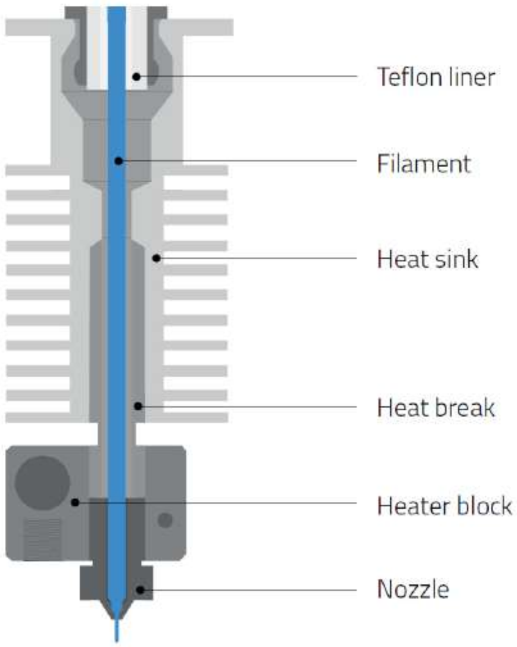


Figure 2.5: Schematic of a hotend (BCN3D (2019))

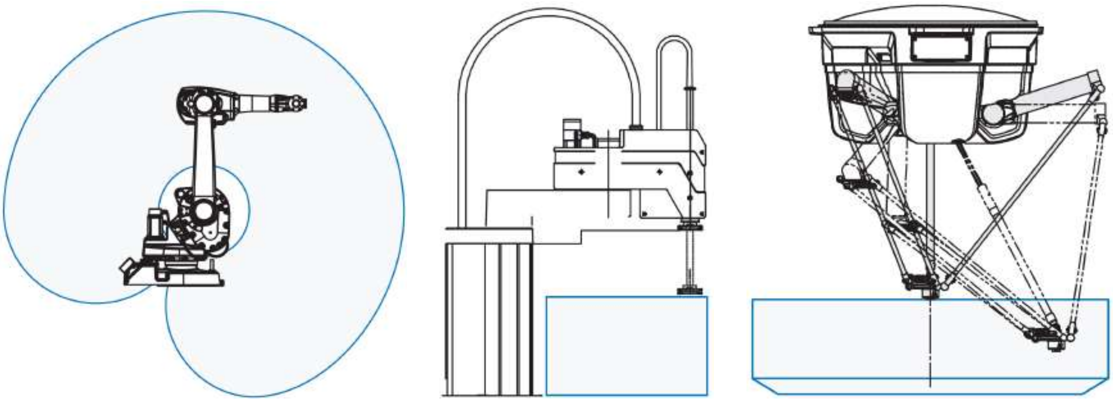
A heat break is included between the heat sink and heater block to prevent heat creep. Since it is made from steel, it has a low thermal conductivity and therefore acts as thermal resistance. The heater block connects the nozzle and heat break. It is made from aluminium to provide high thermal conductivity and accommodates a heater cartridge and thermistor. These components are indicated in figure 2.5 by a large dark grey circle on the heater block for the heater cartridge and a small circle for the thermistor. The heater cartridge provides heat, while the thermistor measures the temperature. The heat sink is located on top of the heat break. It dissipates heat via a large surface area provided by fins and is sometimes cooled by a fan. The filament is guided by a Teflon liner, which provides a low friction surface to prevent filament jamming.

2.2 Industrial Robots

An industrial robot has the task of guiding an end-effector in three-dimensional space. The effector can, for example, be a gripper, a measuring tip or a machining tool. The effector is the part of the robot arm that makes contact with the environment to pick up workpieces, process them and more. A characteristic point of the effector, the tool tip, is called tool centre point (TCP) (Weber (2019)). A key feature of industrial robots is the number of controlled axes and the kinematics design, which can be configured from a combination of translational and rotational axes. Up to six degrees of freedom, three translatory for positioning and three rotatory for orientation of a body, can be realised. At least one mechanical axis must be provided for each required degree of freedom of handling devices. For robots with more than six mechanical axes, redundant additional axes usually extend the working space. Movements in individual degrees of freedom are made possible by the mechanical and control coupling of several mechanical axes. Both translational and rotational axes can be used as main axes. The secondary axes usually have the function of establishing the desired orientation of the gripper or tool. Rotatory axes are always required for this purpose. The working space describes the movement possibilities of a handling device. This space can be reached by the totality of all axis movements with the robot-side mounting flange for tools (Brecher & Weck (2021)).

It is distinguished between three main types of industrial robots. Two are serial kinematics, the third are parallel kinematics. A serial robot consists of a series of arm parts connected by joints, called axis. The effector can be seen as the last arm part. Serial kinematics are divided into vertical and horizontal arm robots (Brecher & Weck (2018)). Figure 2.6 shows the three types with their working spaces. A serial vertical robot can be seen in figure 2.6 (b), and a parallel robot in (c).

The serial vertical robot is the most popular. It is offered in many variants and performance classes due to its wide range of applications. The construction, as seen in figure 2.6 (a), consists of six rotary axes driven by three-phase servo motors with an integrated holding brake. The six axes make the robot universally applicable as they offer the possibility of positioning its end effector with six degrees of freedom. The accessible work area of the robot can be seen in figure 2.6 (a) in blue. Planetary gears amplify the motor torque. Angle detection is carried out with a digital incremental rotary encoder on the motor shaft. Therefore the axis must be referenced during the initial startup. The robot is either freely programmable or manually controllable by an operating device in all degrees of freedom (Brecher & Weck (2021)).



(a) (b) (c)

Figure 2.6: Types of robots by kinematic (Brecher & Weck (2021)). (a) serial horizontal robot, (b) serial vertical robot , (c) parallel robot

2.2.1 Coordinate Systems

It is necessary to define coordinate systems in the workspace and reference points on the industrial robot, in order to describe the motion operations of the robot. They form the basis for the unambiguous definition of movement instructions in the program of the industrial robot. Different coordinate systems are used depending on the handling task to be solved. Joint coordinates describe the spatial arrangement of the industrial robot joints in relation to a local, immovable coordinate origin in the axis. The current position of a robot can be described with the rotation angles around this coordinate axis or as a position displacement from the coordinate zero point in the case of translational actuators. World coordinates define the position and orientation of the TCP in relation to a robot base coordinate system. Generally, this base coordinate system is centred on the placement surface of the industrial robot. The definition of a tool coordinate system is a prerequisite for programming handling tasks using Cartesian coordinates. The tool coordinate system originates in the TCP (Brecher & Weck (2021)).

2.2.2 Types of Movement

Motion commands belong to the basic instructions for industrial robot controllers. Three main categories of motion types are distinguished. In Point to Point (PTP), the robot moves from the actual position to the target position of the TCP along any path in space. Only the starting point and target point are specified in detail in a PTP movement. The robot axes reach their target positions considering the axis-specific accelerations and velocities. The individual axis movements are commonly executed synchronously so that all robot axes reach their target positions together. To do this, the industrial robot controller must determine the guide axis that requires the longest movement time. The other axes are then moved at reduced axis speed or acceleration. In linear movement, the orientation of the TCP is specified. The connecting path between the actual and target position is specified. The movement is performed with defined acceleration. In circular interpolation, three points in the workspace are defined. The three points define a unique circular path (Brecher & Weck (2021)).

2.2.3 Characteristics of Industrial Robots

Guideline VDI 2861 defines the relevant characteristics of industrial robots. The characteristics will be explained in the following, explanations refer to Maier (2019). The characteristics are categorised into geometric, load, accuracy and kinematic characteristics. Essential geometric characteristics are working space and collision space. The working space is the area where the robot interacts with its environment as planned by the operator, and the collision space is the area that cannot be entered by the robot, as it would lead to contact with objects in the periphery.

The relevant parameters of the load characteristics provide information about the maximum possible loads at the flange to the end effector due to mass and the resulting inertia against accelerations or torque due to the inertia of tools or workpieces. It is essential to consider the load to which the maximum travel speed and acceleration of the axes of motion or the effector are still possible.

Accuracy characteristics include position accuracy and repeatability. The parameter position accuracy indicates how precisely a target point is approached. Repeatability is the average distance between target points when the robot approaches the same target point in several attempts. The parameter indicates the positioning precision with which the effector can return to a specific position.

Parameters of kinematic characteristics concern the possible velocities and accelerations of the axes. The parameters for accuracy, dynamics and load strongly depend on each other. When a robot approaches a position, overshooting occurs. The faster a robot moves, the more vibration occurs, and the more the robot oscillates into its final position. The system then approaches the target position more and more precisely within a required stabilisation time.

2.2.4 Gripping Technologies

The following section is based on explanations provided by Hesse (2011). Gripping devices can be categorised into force-locking, form-locking and chemical bond types. Force-locking grips use contact between the gripper and the object to generate a resulting force. Frictional forces, vacuum or magnetic forces are responsible for gripping. In a form-fitting grip, the position is ensured solely by a form-fit enclosure of gripper jaws and object. The object lies loosely between the gripper jaws. Only slight contact forces act on the object, caused by gravitational effects. Form-fit gripping usually requires more jaw stroke when opening the gripper than is the case with force-fit gripping. Chemical bond grippers use atomic or molecular forces such as adhesives or liquid bridges. The mechanisms of gripping due to force is shown in figure 2.7 and can be categorised into force-lock (a), vacuum (b) and magnetic gripping (c) (Hesse (2011)). For this thesis, grippers that act due to the exertion of force are relevant. Therefore these will be described in more detail in the following.

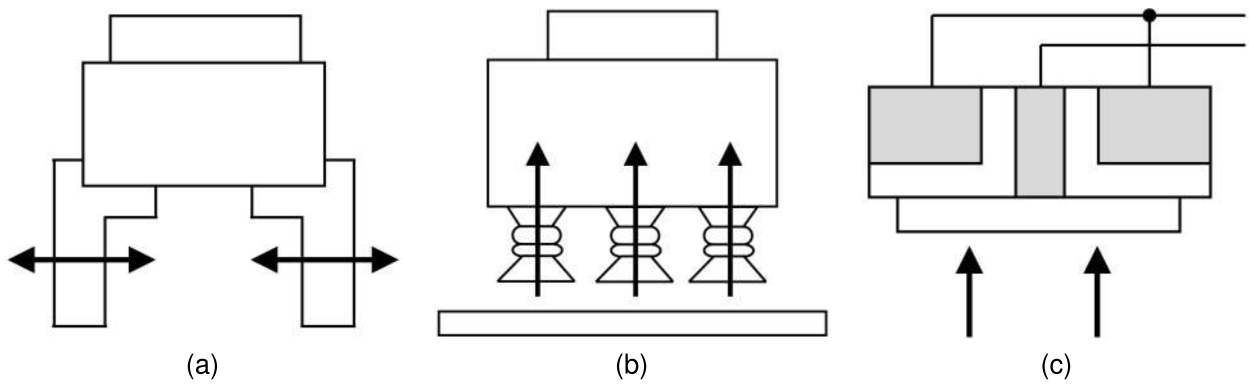


Figure 2.7: Types of gripping mechanisms after (Hesse (2011)). (a) Force-lock gripping, (b) Vacuum gripping , (c) Magnetic gripping

2.2.4.1 State of Order

The critical figure state of order expresses how many components of the orientation and position of a body are known. The orientation of a body is defined by its three rotational degrees of freedom. Its position is defined by the three translational degrees of freedom. The state of order is defined by the formula $OZ = OG/PG$. OG stands for the rotational degrees of freedom, PG demonstrates the translational degrees of freedom. A body with $OZ = 0/0$ is completely disordered. In cases with $0/0 < OZ < 3/3$, objects are partially ordered and objects with $OZ = 3/3$ are fully ordered (Hesse (2020)). One goal of handling procedures like gripping is to achieve a state of 3/3 for the gripping objects.

2.2.4.2 Force-lock Gripping

Force lock-gripping is achieved by clamping. A gripping object is clamped between fixed jaws by the application of forces. The clamping force induces friction force that causes the object to stay fixated. A high coefficient of friction increases the friction forces and thereby the safety of the grip. It is preferable to design the gripping device to fit the gripping objects. In the case of pure force pairing through frictional forces, misalignment of the gripping object's position or orientation can occur during the gripping process or transportation. A form pairing created by gripper jaws adapted to the workpiece contour is safer and needs less gripping force. In general, the object's centre of mass plus the end effector should be as close as possible to the robot to reduce the effects caused by inertial forces during movement. Clamping grippers can be designed as internal or external grippers. To set mechanical gripping elements in motion, actuators are needed. Pneumatic actuators are used frequently because of their simplicity. Another option are electro-mechanical actuators, mainly in the form of motor-spindle systems. The force transfer from the actuator to the jaw can, for example, be achieved by hinge mechanisms, screw gears or wedge drives. The jaws of mechanical grippers must be guided linear or rotational in the gripper housing. Linear sliding guides or rolling guides are used. Rolling guides can be used as linear ball bearings or needle bearings. The main movement principles of gripping claws are parallel movement or movement on a circular path. Gripping devices that feature more than one movable claw need to synchronise the motion of the claws, as the contact point of the claws needs to be the same in every movement. Generally, a gripping point in the centre of the device is desired. Multiple solutions like threaded spindles, gears or wedge drives are used to synchronise the movement.

2.2.4.3 Vacuum Gripping

Gripping and holding objects with negative overpressure is widely used in handling technology. The grippers do not require moving elements and are available in many standard designs at a low cost. Vacuum cups can produce large holding forces. The holding force is a function of suction area size and negative overpressure. Sealing elements isolate the suction cup from the ambient pressure, thus ensuring force transmission. Ideally, the suction cup sits above the centre of gravity of the gripping object. This results in a constant line load at the suction cup sealing lip. Sufficient tightness is required to ensure the upkeep of the vertical force with a suction element. When horizontal forces are applied, the sealing force ultimately causes friction between the suction element and the object. There can be two failure cases: a too small load on the sealing area or a too low friction coefficient.

2.2.4.4 Magnetic Gripping

Magnetic grippers can be in the form of a permanent magnet or an electromagnet. In the case of permanent magnet grippers, the part can be released by applying an opposing magnetic field. A ferromagnetic gripping object can be released by moving the magnetic field away from the object. This is frequently achieved by a pneumatic cylinder that moves the magnet. Electromagnetic grippers hold a workpiece through intermolecular forces generated when the current is switched on. Because of the low holding force and the humming of AC magnets, DC magnets are used almost exclusively.

2.3 Transversal Flux Machine

TFM are single-phased, permanently excited synchronous machines with a high number of poles. The name is derived from the direction of the magnetic flux, which is transversal to the direction of motion. The design of the machine allows the magnetic and electrical circuits to be decoupled. Due to the high number of pole pairs, the TFM is a slow-running machine with the ability to produce high torques, making it ideal as a gearless direct drive (Schmid (2011)).

2.4 VDI 2221

This section explains the relevant parts of directive VDI 2221 (Verein deutscher Ingenieure (2019)). The directive VDI 2221 deals with generally valid, industry-independent fundamentals of methodical development and design. It defines work stages and results, which can be a guideline for a development process due to their general relevance. The overall procedure is divided into nine steps to structure design processes, producing nine corresponding work results. Depending on the task, these steps are iterated.

The first step is called Clarifying and itemising the problem or task. The requirements of customers or product planners are formulated and documented. Information about the project and challenges are collected. The result of step one is a list of requirements, which is the foundation for all further development steps. This list is reviewed and adapted on an ongoing basis.

The next step is determining functions and their structures. It is precisely defined, what the invention should be capable of. Further the functions to achieve this goal are defined. The total number of subfunctions defines the overall function of the product.

In a third step, the solution principles and their structures for the previously defined functions are searched. Therefore some natural, physical or other effect has to be selected. It is then analysed if the chosen effect can be realised effectively. The structure of each partial function can then be combined to form the overall concept. To support this process, strategies like morphological box can be applied. The work result represents a selection of principle solutions. As a rule, several solution paths are selected in order to be able to make a selection of the optimal solution. A combination of different solution parts is also possible.

Following is a comparison of the results with the formulated requirements. It is searched for the most promising solution that meets the requirements. Methods like benefit analysis or SWOT analysis can be used to make a methodical choice. After a mathematical or verbal comparison of solutions, one concept is chosen for further development.

In step five, the selected solution is broken down into realisable modules. The result of the step is a modular structure. In contrast to the functional structure or effect structure, it already shows the division of the solution into groups and elements essential for its realisation, including their links. At this stage of work, product development often branches out into parallel construction lines, which proceed independently.

The step of designing the modules specifies the concepts. Therefore CAD Models, sketches or data models are developed.

Step seven combines the solutions for subfunctions by integrating the product as a whole. During integration, the already pre-designed modules are finalised and merged into one product by adding further details, by designing and adding groups and elements that have not yet been processed, and by linking all groups and parts. This is the final design stage. The result of the work is an overall design that contains all the essential design specifications for product realisation. Forms of presentation are mainly technical drawings, elaborated CAD models or preliminary parts lists.

The following step, elaborating the details of execution and use, overlaps with previous activities as specifications for the technical production realisation and product usage have already been made during these activities. The work result is the product documentation with manufacturing, usage and certification information. This can be in the form of technical drawings, CAD models or other documentation.

Lastly, the assurance of the fulfilment of the requirements is carried out. The result and list of requirements are compared. Calculations, simulations, and trial or test activities of a development project are performed. A distinction can be made between verification and validation. Verification is the analysis of whether a developed product complies with the requirements in the specification. Validation is the analysis if the product is suitable for its intended use or whether it meets the needs of the user or customer.

3 State of the Art

The following chapter will cover the state of the art of manufacturing processes which build the foundation of the concept of the 4K-FFF unit, including hybrid manufacturing and production of function-integrated parts. Afterwards, the basics of threaded inserts and the methods to include them in parts are illustrated. Furthermore, the 4K-FFF unit will be introduced. From the state of the art a need for continued research is derived.

3.1 Hybrid Processes in additive Manufacturing

The "International Academy for Production Engineering" (CIRP) defined hybrid processes as follows: "Hybrid manufacturing processes are based on the simultaneous and controlled interaction of process mechanisms and/or energy sources/tools having a significant effect on the process performance" (Lauwers et al. (2014)). Simultaneous and controlled interaction means the processes occur in the same area and shortly after the previous process. The authors give two examples for a better understanding of the definition. The first example is laser-assisted cutting. This procedure uses laser beams to soften the material and a cutting tool to machine the part. By combining both technologies, more efficient machining is possible. The second example is curved profile extrusion. Here the material gets bent directly after the extrusion, whereas in the standard procedure, both steps are separated and performed with a time delay. This chapter will focus on hybrid manufacturing methods that combine additive and subtractive manufacturing, as this method is used in the 4K-FFF unit.

Hybrid processes combine the advantages of conventional and additive manufacturing and offer great potential. The advantages of additive manufacturing like high flexibility in the design process, decentralised manufacturing and less waste product due to production from a solid body are maintained in hybrid processes (Awiszus et al. (2012)). Conventional manufacturing can compensate for defects like inaccuracies, pores or residual stress, which frequently occur in additive manufacturing (Gibson et al. (2021)).

3.1.1 Metal hybrid Processing

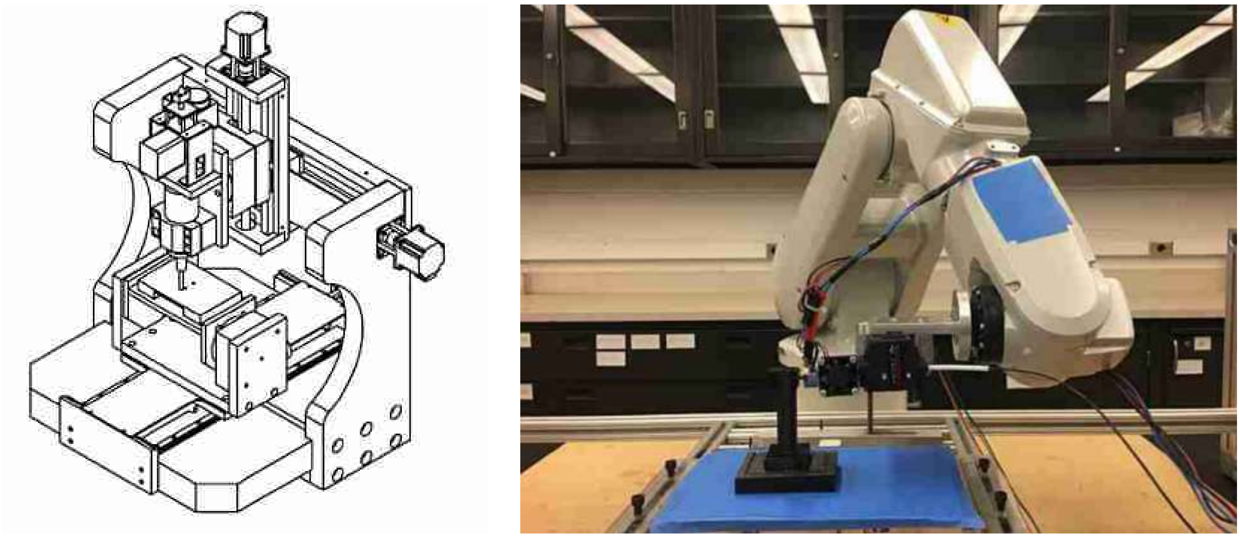
The combination of additive and subtractive methods can be used to improve surface quality and dimensional accuracy. Therefore different kinds of hybrid processes have been developed.

The process of DED is explained in 2.1.2.2. This additive process can be followed by secondary steps, like rolling and analogous forging, laser shock peening, shot peening and CNC machining. Rolling and analogous forging processes are used to treat the surface and release stress in the material. It leads to a refined microstructure, minimises porosity and reduces distortion. Shock peening uses beads to plastic deform the surface of the produced part, which leads to improved hardness and reduced roughness. Laser shock peening uses high temperatures and pressure. Plasma is formed on the outer surface and generates a shock wave that travels into the part resulting in plastic deformation. The deformation results in an altered stress state by inducing compressive stress. This method can be used to adjust the stress state on the surface to the desired point. An essential secondary process is the CNC machining process. It can be used for two main applications. One is to mill the surface between two added layers to guarantee a constant layer thickness. The second is called end milling, here the finished product is milled to improve the accuracy and surface finish of the part. With CNC processes mostly milling and rarely turning is used as a second step to additive manufacturing (Dilberoglu et al. (2021)).

3.1.2 Plastic hybrid Processing

The common technology used for plastic hybrid manufacturing is FFF. Problems that need to be addressed are thermal shrinkage, chordal errors, staircase effects and support structure burrs. Therefore much research is performed to improve these areas. Techniques are developed to improve the surface quality and accuracy, for example, laser-assisted finishing, hot air jet polishing and CNC machining (Dilberoglu et al. (2021)). One example of a combination of FFF with CNC milling is given by (Lee & Chung (2013)). The installation can be seen in figure 3.1 (a). A 5-axis mechanism is developed that has unique feature that the milling head and the filament extruder sit on one axis that rotates 180 degrees to switch between milling and extruding without an additional actuation system. The research aims to improve the error in the outer dimensions of 3D-printed parts compared to the predefined values. An order of magnitude improvement is achieved.

Another example of hybrid processing combining additive and subjective methods is given by Li, Haghighi & Yang (2018). In this approach an industrial robot with 6 degrees of freedom and two different toolheads is used. One head each is used for subtractive and one for additive manufacturing. This method's unique feature is nonlinear toolpathing to improve the process. The setup can be seen in figure 3.1 (b). In the shown configuration, the additive head is printing from the side. The authors conclude that the hybrid process reduces material waste, needs less production time and improves surface quality compared to similar processes.



(a) (b)

Figure 3.1: Plastic hybrid processes. a) Hybrid 5-axis machine tool with FFF (Lee & Chung (2013)), b) Robotic arm with FFF extruder and mill (Li, Haghighi & Yang (2018)

Apart from academic approaches, the companies Enomoto and Thermwood offer commercially available machines (Enomoto (2022), Thermwood (2022)). The Japanese company Enomoto states that combining FFF and cutting eliminates the need for setup changes and post-processing. Production time can be drastically shortened, and production costs can be reduced. Depending on the requirements, the surface roughness of the cutting process can be selected as needed. By specifying the cutting location, high-precision and smooth surface finishing is possible (Enomoto (2022)). The company Thermwood offers the Thermwood LSAM 1540. Its name stands for large-scale additive manufacturing, the number is derived from the dimensions of the build platform, which is 40 x 15 feet for this model, which equals 12,2 x 4,6 meters. The machine is capable of printing and trimming on the same machine (Thermwood (2022)).

3.2 Function integrating Manufacturing Processes

Additive manufactured structures can be turned into functional mechatronic devices called function-integrated parts by adding sensors, actuators and electronics. Furthermore, mechanical components like threaded inserts can be included to increase interconnectivity. To produce function-integrated parts, conducting material and installation of external components is used. The characteristic feature of these procedures is that the external components and the part are merged in a single process, where the part embeds the external component. They are combined by conductive connections and form one coherent unit that cannot be separated. The layer-by-layer production of additive manufactured parts allows access to the inner geometry of a part in its build process. Therefore external components like motors, sensors, circuit boards or threaded inserts can be included in the internal structure of the part. These external components will be generally called inserts from now on. These inserts can be used to produce complex mechatronic systems, these systems are also called Mechatronic Integrated Device (MID). The printing process needs to be paused to install the insert into the part. After the insert has been installed, the printing process is continued. When continuing the process, the insert cannot be taller than the highest layer. Otherwise print head and insert could collide. Therefore the upper surface of the insert needs to be flat, or shape converters can be used, which makes the process more complex.

Conductive traces are the key to connecting the parts to its surrounding, connecting the inserts in the part itself and to print circuits. The four methods to produce conductive connections are the usage of conductive pastes, surface deposition, conductive polymers and implemented wires. Conductive pastes can be used on both planar and non-planar surfaces. A dispensing device is required for application. After application, the paste usually has to be cured. For surface deposition, processes such as aerosol jetting are used. A tool head is required for this. Not all materials are compatible with these processes, as high temperatures can occur. The advantage of using conductive polymers is that existing infrastructure can be used for these applications. They are compatible with conventional 3D printers and can therefore be used without investment cost. Dual extrusion systems are frequently used to print structural and functional sections of a part. Implemented wires offer low material costs and several usable materials. No thermal post-processing is required. Furthermore, wires have a low resistance (Ziervogel et al. (2021)).

The following chapter explains different kinds of procedures, which aim to produce function-integrated parts.

3.2.1 Integration of electrical Circuits and Components

Coronel et al. (2017) present an additive manufacturing system that can be seen in figure 3.2. It consists of two FFF printers, one CNC router and an industrial robot. This industrial robot connects the other systems, as it can transport the build plate from one system to the other. The FFF printers are used to manufacture the main body, the CNC router is used for subtractive manufacturing. Furthermore, the CNC router has a pick and place component capable of foil and wire embedding to include either conductive foils or wires into the assembly. The authors show multiple cases where the system's capabilities are used to manufacture complex electrical devices. It is concluded that hybrid manufacturing significantly improves the functionality of additive manufacturing processes and therefore has great potential, although more research is needed.

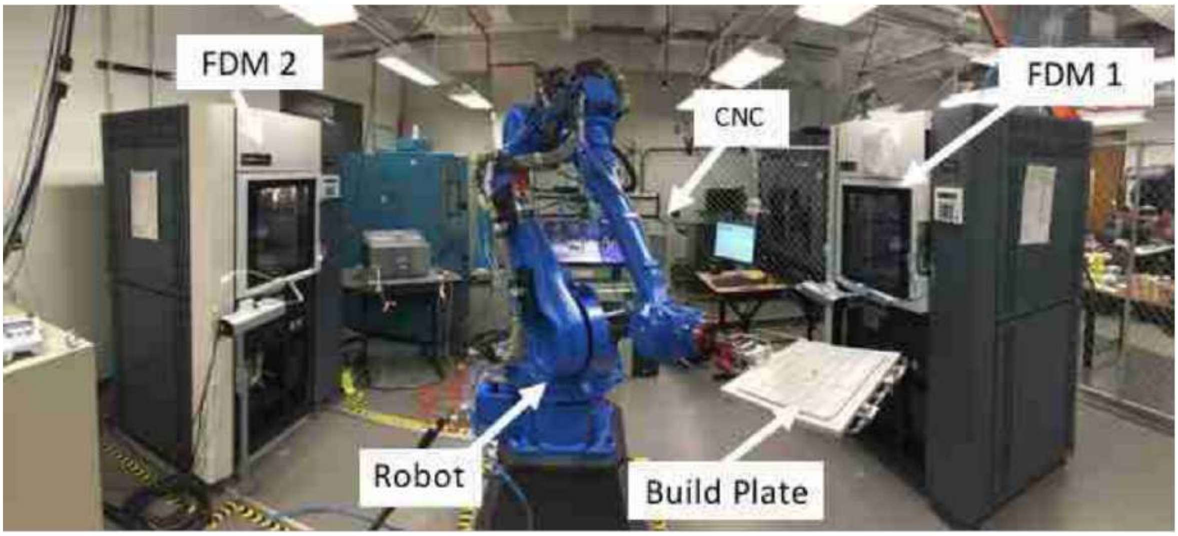


Figure 3.2: Multi3D system (Coronel et al. (2017))

Espalin et al. (2014) developed another system consisting of two FFF machines connected by a sliding platform with the mounted building platform. Between the two FFF machines, a middle compartment with a CNC router is located that allows subtractive manufacturing and deposing of conductive inks. Figure 3.3 shows the process used. At first, the main body is produced with FFF, and the cavities and interconnections are formed using the CNC router. The following steps are deposing of conductive ink and installation of external components into the cavities. Finally, the ink is thermally cured. The external components are applied manually, although an automatic placement is investigated. This should be accomplished by a pick and place unit on the CNC router. Furthermore, a wire embedding module is planned. A CubeSat module with micro-scale features is manufactured to evaluate the system's functionality. It is concluded that subtractive manufacturing significantly improves the accuracy of the FFF processes and leads to better interconnected channels.

Ankenbrand, Eiche & Franke (2019) present a procedure where piezojet printing, FFF and a pick and place system are combined to manufacture MID. The authors use conductive ink

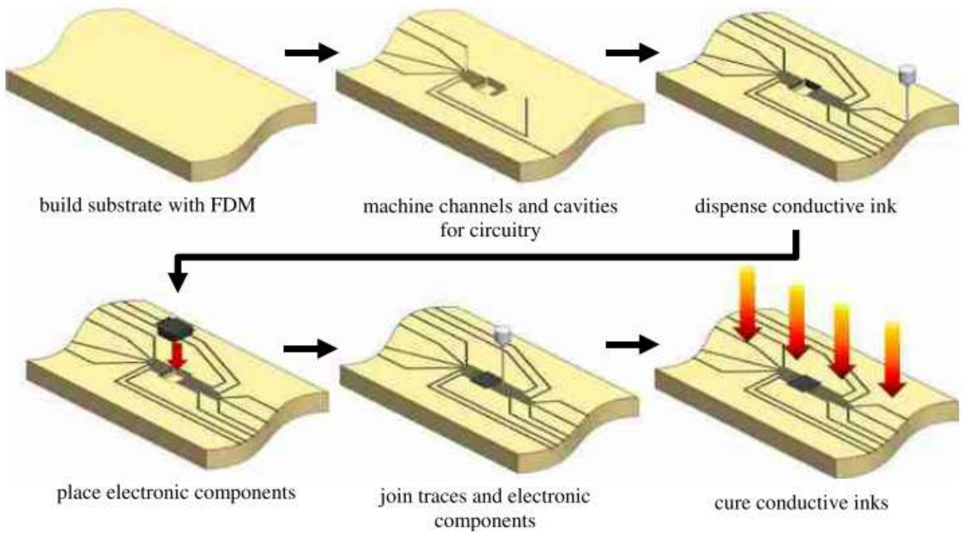


Figure 3.3: Process steps for 3D printed MIDs with conductive ink (Espalin et al. (2014))

with silver particles as a conductive connection. The main body is produced with FFF and PLA. A vacuum nozzle is used to pick up components from a pick and place module and places them into the conductive ink. With their procedure, the authors managed to create three-dimensional circuits. One observed challenge is smearing due to the same height of two extruder systems. To prevent issues caused by this, walls were added between conductive tracks. In figure 3.4 a X-ray of the finished circuit can be seen. An area with a short circuit is highlighted. To achieve good printing results, the authors recommend a cleaning procedure before every start of each additive process. Furthermore, a camera system for process monitoring and optimised pick and place is advised.

Wasserfall (2015) shows a 3D printing system that is optimised for low cost. It uses a construction consisting of a commercially available FFF printer, an extruder for conductive paste, a vacuum nozzle for pick and place and a camera system to precisely align components, which costs around 1000€. Several different electronic devices are created with this setup, proving that low-cost assemblies can produce complex function-integrated parts.

The ease of automation and integration into existing FFF procedures through dual extruding, show that conductive filaments have a high potential in producing function-integrated parts. One focus point in research is parameter optimisation, and another is the development of new conductive filaments.

Barši Palmić, Slavič & Boltežar (2020) investigate the influence of printing parameters on the performance of electrical conductors. Layer height, trace spacing, extrusion rate, nozzle

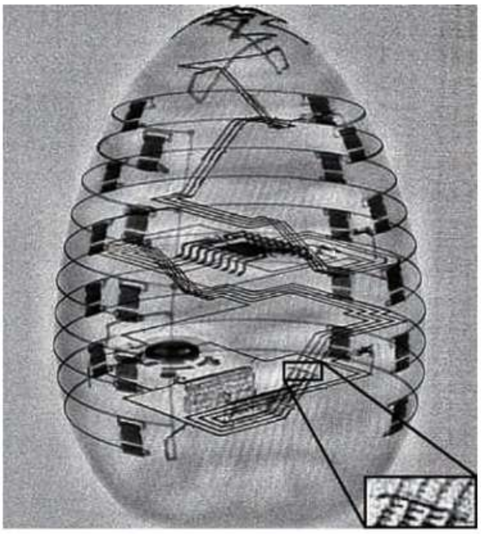


Figure 3.4: X-Ray of three dimensional circuit demonstrator (Ankenbrand, Eiche & Franke (2019))

temperature and heat bed temperature are critical parameters for the resistance of the conductors. The printing speed does not have a significant influence on the resistance.

Flowers et al. (2017) compare carbon black, graphene and copper filaments. Copper has the best bending capabilities, whereas graphene and carbon black conductors are brittle. Of the compared materials, the copper filament (Electrifi) has the lowest impedance, the graphene filament (Black magic) is the second best, and the Carbon Black filament (Proto Pasta) has the worst impedance values with an order of magnitude difference. Additionally, the authors investigate the influence of length and diameter on resistance in conductors. Different probes with the same length and modified cross-section are analysed. It shows that a bigger cross-section leads to lower resistance. The copper filament (Electrifi) has the lowest resistance, the graphene filament (Black magic) is second best, and the Carbon Black filament (Proto Pasta) has the worst resistance values. The copper filament is chosen for further experiments. A fully 3D printed high pass filter is manufactured by combining 3D printed resistors, capacitors and inductors to prove the viability of FFF in producing electronic components.

3.2.2 Environmental Benefits of Function integrating Manufacturing Processes

The advantages of additive processes that benefit their environmental impact can be transferred to producing function-integrated components with additive methods. The advantages of additive manufacturing are material efficiency, resource efficiency, production flexibility, and component design flexibility. In contrast to subtractive methods, additive methods only require the amount of material that ultimately forms the component volume, plus any support structures. Conventional manufacturing often requires additional tools and coolants that continue to consume resources and generate emissions and waste. On the other hand, additive manufacturing uses fewer resources and therefore has a minor environmental impact. Flexibility in the production location allows for decentralised production of components and manufacturing close to the customer, reducing emissions from transportation. The flexibility of production enables rapid changeover between product designs without high costs or adjustments to the plant (Walter & Marcham (2020)).

In addition to the advantages of additive manufacturing, the automation of the process can be beneficial. Automation of the process supports the economical operation of the equipment, making the product cost-competitive. The energy efficiency of the process increases with higher levels of automation. Consistent operation of a plant ensures product quality and minimises waste. Finally, the service life of a product can be increased through continuous process monitoring (Litz (2005)).

Further advantages arise from the production of function-integrated components. Printed circuit boards are generally made from duroplasts that are difficult to recycle. The thermoplastics used in the production of function-integrated components are easier to recycle. In addition, disposal of the components is less critical. Miniaturisation and reduction in the number of components leads to increased raw material efficiency. Fewer downstream assembly steps are required, reducing transportation costs and emissions (Schüle (2020)).

3.3 Threaded Inserts

Threaded inserts are cylindrical-shaped metal parts that can be included in cavities in plastic assemblies. On the outside, a knurl pattern prevents pull out and torque out of the insert (Pencom (2014)). The threads provide durable and reusable joints. Many different kinds of inserts are available. They can be classified by their installation technique. It is distinguished between ultrasonic, heat, mould in, and press-in inserts (Gallagher (2018)). Furthermore, the inserts can be classified by the used material. Common materials are brass and stainless steel (Pasko (2009)). These variations will be discussed in the following chapter. Furthermore, the different knurl patterns will be described. Another focus will be the known processes for integration. The manual, as well as the automated procedure, are explained.

3.3.1 Types of threaded Inserts

Heat staking inserts are installed by pressing the insert into a preformed hole while simultaneously heating the insert. The hole's perimeter softens and flows into the inserts knurl pattern to form a solid bond. Ultrasonic inserts are installed by pressing the inserts into a preformed hole. With ultrasonic equipment, vibration is applied, which causes frictional heat that softens or melts the hole's surroundings. After installation, the plastic cures and forms a solid bond. Moulded-in inserts are installed during the moulding process. They are held in the cavity by core pins, which are removed while demolding. The inserts are encapsulated in the plastic, only the thread is exposed. Press-in inserts are installed into preformed holes by pressing them in without melting or softening the surrounding material (Gallagher (2018)).

The required equipment for heat staking inserts is a device that is capable of applying force and heat at the same time. Ultrasonic inserts require specialised ultrasonic installation equipment that can vibrate and apply force simultaneously. Mould-in inserts do not require special equipment apart from the core pins and equipment needed for moulding. Press-in inserts require a press than can apply force (Gallagher (2018)).

Knurls are used to increase torque and force resistance. Rougher knurls do increase torque resistance, but they also cause greater stresses in the plastic. Compared to straight knurls, slanted knurls reduce torque resistance but increase axial pull-out forces. In practice, knurls with an angle between 30° and 40° positively affect pull-out forces, with a minimal loss of torque. Some knurls combine different angles on the same insert to achieve an optimal combination of torque resistance and pull-out strength (SPIROL (2020)). The pull-out force is the required force to pull the insert out of the host material, the torque resistance is the required torque to rotate the insert in the surrounding material (Gallagher (2018)). The insert length significantly impacts pull-out and torque-out strength (Pencom (2014)).

Another aspect to consider in insert design and selection is the shape of the hole, except for mould in inserts, where no predefined hole exists. It is distinguished between tapered holes and straight holes. The correct hole diameter has a critical impact on the performance of the insert. Oversized holes reduce functionality as they reduce pull-out and torque-out strength. Too small holes cause unwanted stress and potential cracks in the plastic. Furthermore, undersized holes can cause burrs on the hole's edge, making the threaded insert more challenging to install (SPIROL (2020)).

Figure 3.5 shows four examples of inserts with different knurl shapes. The knurl on (a) is diamond shaped knurl on a mould-in insert. Figure 3.5 (b) shows an insert suitable for heat or ultrasonic installation. It has two slanted knurls with opposing angles and is designed for straight holes. This design is commonly used as it offers a good compromise between pull-out and torque-out strength (Gallagher (2018)). In contrast, figure 3.5 (d) shows an insert for heat or ultrasonic installation in tapered holes. It has a straight knurl in the top region with a slanted knurl in the middle. This knurl offers better performance in torque out strength while sacrificing pull-out strength. Figure 3.5 (c) shows a press-in insert with a diamond knurl for straight holes.

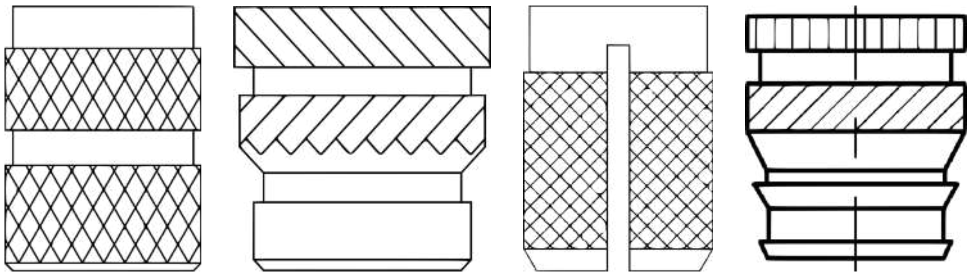


Figure 3.5: Different kinds of inserts and knurl patterns. (a), (b) and (c): Pencom (2014), (d): SPIROL (2020)

3.3.1.1 Selection of Inserts

As an installation method, press-in inserts are unsuitable since applying relatively high force is necessary to install them. This could lead to the unsticking of the component from the print bed. Mould-in inserts are specifically designed for moulding applications and are therefore unsuited. Ultrasonic installation requires special equipment, which can take a lot of space and is costly. Furthermore, the vibration could lead to the unsticking of the component from the print bed. Heat staking inserts provide a reliable and cost-efficient way to install threaded inserts. The only disadvantage is a slightly slower installation time compared to ultrasonic inserts (Jeznach (2013)). For these reasons, heat staking is chosen as the application method.

A second choice in the selection of inserts is the material used to manufacture the insert. The two standard materials are stainless steel and brass. The raw material cost does not differ heavily, but steel's machining cost is higher than brass's. Furthermore, steel is less heat conducting, leading to a slower installation time than brass. The advantage of steel inserts is superior performance in aggressive environments (Pasko (2009)). As the produced parts will not be used in an aggressive environment and brass inserts are favourable concerning price and conductive properties, brass is chosen as material.

The knurl is chosen according to the recommendations mentioned above. In general, two slanted knurls with opposing angles provide a good combination of pull-out strength and torque resistance. Therefore this type of knurl is chosen.

3.3.2 Manual Installation

This section covers the manual installation of heat staking inserts, as they are the chosen type for this thesis. There are two methods of transferring heat to the threaded insert. The first method uses a heated tip that transfers heat to a threaded insert manually placed into the hole. The second uses a preheated chamber that heats the threaded insert to the required temperature. In this procedure, the installation is done with a non-heated tip (SPIROL (2020)).

With the rising popularity of FFF in home applications, threaded inserts are becoming more common. For these non-professional appliances, the simplest way of installation that does not need special equipment is to use a soldering iron for the implementation. The insert is placed in the hole. Then a soldering iron is used to heat the metal and to apply pressure until the insert is installed. This procedure is described in a guide by CNC Kitchen (2019a). The popularity of threaded inserts in home applications is demonstrated by the many more guides that are available online on how to apply threaded inserts, like clevercreations (2022), MakerBot (2022) or Vasquez (2019). Furthermore, the topic's popularity can be seen by the viewer counts of video guides covering the subject. A popular video guide by CNC Kitchen (2019b) that compares different kinds of threaded inserts has more than 1.6 million views. Another guide that analyses the strength of 3D printed inserts and compares them to threads directly cut into plastic shows a viewer count of 1.3 million (CNC Kitchen (2019c)). For the improved application of inserts with a soldering iron, specialised soldering tips are provided by companies like ruthex (2022). These soldering tips offer a flat contact area and a guiding pin.

The design prevents tilting and therefore simplifies the installation. The tip of the soldering iron needs to be adapted after each change of the insert size.

A advanced way of installation is to use a thermal press. Multiple companies offer similar devices with a heating element that is guided. Due to the guide, it has only one degree of freedom, which is the axial direction of the insert. This prevents tilting of the insert. These machines are normally equipped with temperature control and adjustable stop. Figure 3.6 shows three examples from various manufacturers. The devices can install different sizes of inserts, although the tip of the heating device has to be adapted manually for every size and needs to be changed if a different insert is to be used. In addition, the inserts have to be placed into the holes manually (Inserco (2022), Tappex (2022), SPIROL (2021)).

Figure 3.6: Machines for manual installation (Inserco (2022), Tappex (2022), SPIROL (2021))

3.3.3 Automated Installation

Inserts can be installed automatically, although the existing machines only allow automated installation for predefined components. If another component is to be handled, the machine has to be adapted manually. Therefore, the existing machines are well suited for large quantity production but not for small series or rapid prototyping. In chapter 3.3.2 the two installation methods were explained. The methods mentioned until now use the first method with direct heating, whereas the automatic processes use the second method with a heating chamber. The task of the machine operator is to load a plastic component into the machine, start the installation process and remove the finished part. Parameters like depth, temperature, force and installation speed are predefined, which leads to repeatable results for every procedure. A vibration feeder or a similar concept sorts the inserts and brings them into the correct orientation. The heating chamber and the sorting device eliminate the need for human interaction with the insert. Figure 3.7 shows the SPIROL model HA, where a vibration feeder can be seen in the back and the heating chamber in the front. Other suppliers are Danrel (2022) and KVT Bielefeld (2022).

Figure 3.7: SPIROL model HA (SPIROL (2021))

Apart from these commercially available solutions, some concepts for installation with industrial robots exist. PTI Engineered Plastics (2022) show an idea similar to the intended use of the tool developed in this thesis. Unfortunately, no documentation is available on the project, so all information is extracted from a promotional video about the design. Figure 3.8 shows the setup of the concept. A heating element similar to a soldering iron is attached to an industrial robot. The industrial robot is programmed to position the heating element in the correct orientation over the insert. It is then waited until the temperature of the heating element reaches its target value. When the temperature is reached, the heating element is moved downwards in a linear movement by the industrial robot to melt the insert in. The force on the heating element is measured to check for failure in the system. The significant difference between the intended use and the presented construction is that in this concept, the inserts have to be placed manually into the holes. Therefore only the melt-in process is automated, but not the whole process.

Further inventions cover the installation of threaded inserts into metal parts. These threaded inserts are used in softer metals, where the thread might wear out. They are screwed into

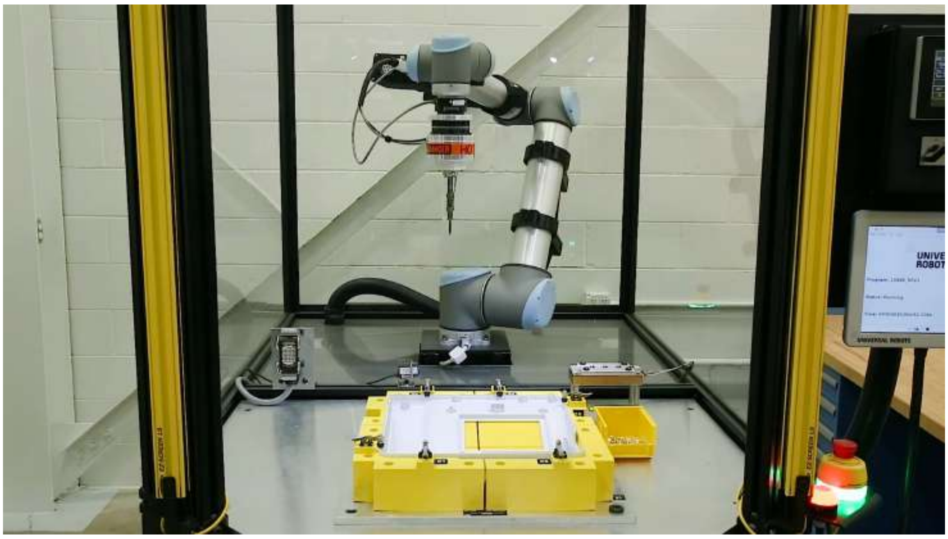


Figure 3.8: MASS-R automated thermal insert machine (PTI Engineered Plastics (2022))

threads of the part. The inserts are made from resilient materials and provide better thread durability (Wittel, Spura & Jannasch (2021)).

Huber, Schoger & Bader (2015) present a method to install these kinds of inserts into metal parts automatically. A specialised tool for installing threaded inserts is mounted on an industrial robot's flange. The tool is capable of screwing. It has a specific socket for threaded inserts. Inserts are fed via a conveyor belt, which features a centring device to ensure correct alignment and centring. The tool picks up the insert. A sensor detects whether the insert is seated correctly. If this is the case, the process continues, and the insert is screwed into the part. These kinds of inserts have a driving pin for installation that has no purpose after installation and needs to be removed. Therefore the driving pin is knocked off by a sudden movement of the tool. This completes the installation process.

Sehrschön & Siegelhuber (2016) propose a similar idea, with a focus on the development of the tool for screwing the insert into the part. A key feature of the tool is the removal of the driving pin and its extraction from the bottom of the cavity. To achieve this, solutions with suction or magnets are investigated. It is found that the insert material, which is not magnetic under normal circumstances, partially magnetises in the forming process. Therefore magnetic extraction is chosen, as it is the more reliable solution. Suction is used for the disposal of the detached driving pin.

Kähler, Eschen & Schüppstuhl (2020) research the automated installation of potted inserts into honeycomb sandwich materials for aircraft interior. Threaded inserts are used as standardised connecting points. One sandwich component can hold up to several hundred inserts. The installation process is mostly done manually due to precise joining tolerances. The process works as follows. First, the insert is placed into a cavity. The insert is attached to an installation cap, which has two holes connected to the honeycomb structure's interior, but not with the interior of the insert. The adhesive is fed through one of the holes until it exits the other hole. After curing the adhesive, the insert is fixated, and the installation cap can be removed. The authors developed an end-effector for an industrial robot capable of gripping and installing potted inserts. One of the challenges is that the insert is gripped at a surface that is not accessible when the insert is in the hole. A spring-loaded mechanism solved this. When the insert is gripped, a spring is preloaded. After precise placement above the hole, the gripping mechanism is released, and the spring presses the insert into the hole. The end-effector features a camera to compensate for the inaccuracy of positioning of the industrial robot. The camera is used for precise positioning via a circle detection algorithm. It was proven that automated installation of potted inserts is possible with the presented setup. However, it was determined that the accuracy of the process does not meet the expected theoretical accuracy. The identified reason for this is low gripping repeatability.

3.4 4K-FFF Unit

The 4K-FFF unit is part of the project "Innovationscampus Mobilität der Zukunft". The project's goal is to produce TFM, explained in chapter 2.3, with additive manufacturing technologies. Therefore three work packages have been defined. The production of stator and rotor are two of them. In the third package, sensors for monitoring the TFM should be developed. Continuous condition monitoring by integrated sensors in the drive system is required throughout the entire utilisation phase to protect the machine components from overheating. Additive manufacturing can be a crucial technology for this purpose, as it can be used to create function-integrated components in a shape that cannot be realised otherwise, or only at a high cost.

In the context of work package three, the 4K FFF unit was developed at the WBK. It currently consists of three movable modules, which can be positioned in relation to each other as required. The modules are a FFF unit, a handling module and a passive module, as pictured in figure 3.10. The system is controlled by a programmable logic controller (PLC) provided by the company Beckhoff. The control concept was developed by A_Kleim (2020). For easier system usage, a software called HybridPlaner was implemented by A_Schulz (2021). It offers a graphical user interface to plan the production process. Therefore, the FFF process can be paused, and handling steps or subtractive manufacturing can be performed. Afterwards, the FFF process is continued. Figure 3.9 shows the process chain of the process as presented by Baranowski et al. (2020). At first, the material and process are prepared. Then the printing process is carried out alternating with handling steps, during which the process is paused. After that, the printing process continues. The two steps are alternated until a part is finished. Following is a post-processing step for the material and the process itself. Lastly, the finished part is inspected.

Figure 3.9: Process chain for the 4K-FFF unit after (Baranowski et al. (2020))

After investigation of the state of the art it was determined that currently no comparable process to the 4K-FFF unit is described in the literature, that has a similar grade of automation, can process conductive material, is capable of subtractive manufacturing and has a handling unit that can cope with various forms of inserts and install them in one additive manufacturing process.

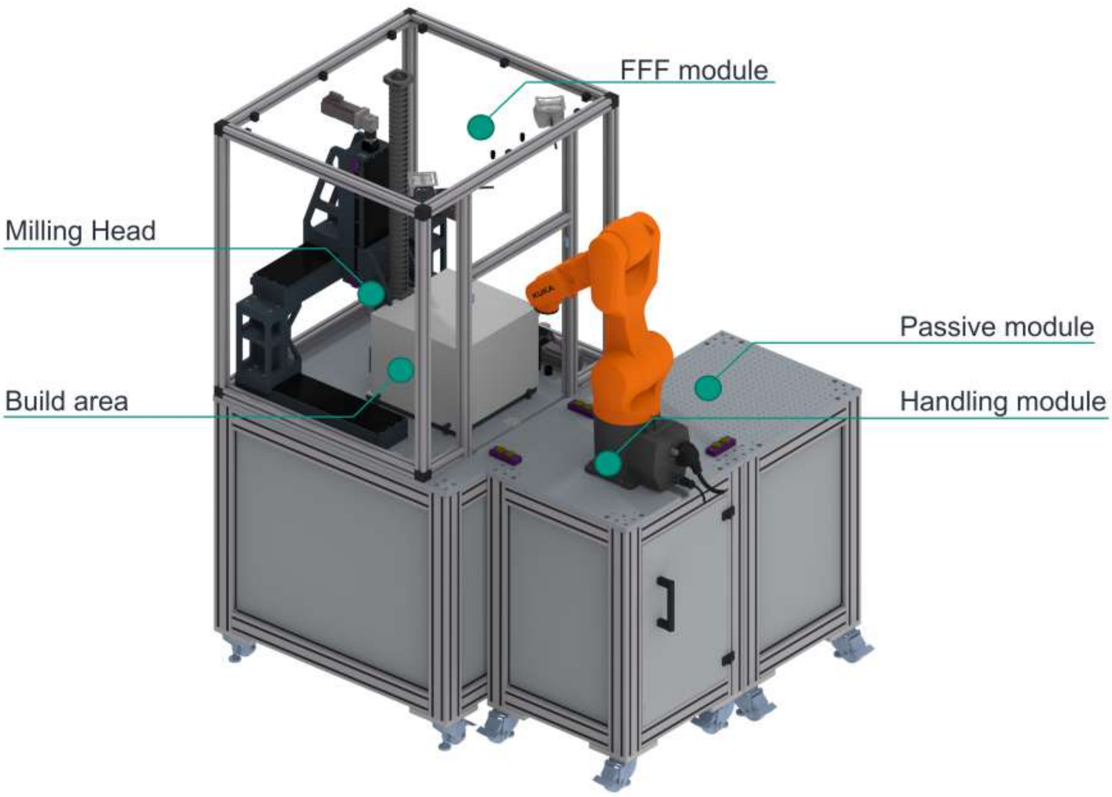


Figure 3.10: 4K-FFF unit

3.4.1 FFF Unit

The general FFF process is explained in chapter 2.1.3. As mentioned, the FFF unit works with a movable printhead in X, Y, and Z direction. The build plate has a size of 300 mm x 300 mm. A maximum build height of 250 mm can be achieved. In addition to the printhead's X, Y and Z movement, the build plate can be rotated. This is not used during the print process but in the insert installation phase. With the rotation, the part is better accessible for the industrial robot. Furthermore, the build plate is heated.

The printhead carries four independent extruders that are usable parallel. The name 4K-FFF unit is derived from this feature. Because of this arrangement, multiple filaments can be utilised in one part. The FFF module was extended by a milling head by A_Schottmüller (2021). It is retractable and extendable to prevent collision between the milling head and the part while printing. The pneumatic system, the PLC and the human interface module are installed on the FFF module.

A transparent housing encloses the print area to seal it from environmental influences. Fan heaters can heat the inside to ensure a constant temperature. A pneumatic door is included in the housing to make the printed parts accessible during the handling process.

3.4.2 Handling Module

The handling module is used to install inserts into the components during the process. A KUKA KR 6 R900-2 industrial robot is used for this purpose. The robot is a serial horizontal six-axis robot with a maximum payload of 6.7 kg. It has a pose repeatability of $\pm$ 0.02mm. A jaw gripper MPG 40, a vacuum gripper ESG-4-SF-HD-QS and a measuring tip are available as effectors. The jaw gripper can be used for less sensitive components. With the vacuum gripper, sensitive electronic components can be gripped and installed. The measuring tip is used to align the coordinate systems of the printer and robot. In addition, the coordinates of the inserts on the passive module can be determined precisely. A collision sensor OPR-048-P00 is attached to the mounting flange to prevent system overload and equipment damage. All effectors are fitted to the collision sensor. Currently, the effectors have to be changed manually. This means that a fully automated process is impossible if more than one effector needs to be used.

3.4.3 Passive Module

Before the start of the process, all inserts are provided on the passive module in specific locations. The alignment has to be correct, and the location has to be stored in the control unit. A thread pattern is provided that can be used to fixate the inserts or mountings for inserts on the module.

3.4.4 Pneumatic Schematic

All of the effectors are actuated by a pneumatic system. As seen in figure 3.11, the pneumatic system can be divided into four categories. The system is categorised into supply for the industrial robot, the pneumatic door, the milling head and a cooling system for the extruders. The cooling for milling head and extruders is not regulated by valves and provides continuous flow. The collision sensor is also under constant pressure. For these outputs, a pressure control valve of type MS2-LR-QS6-D6-AR-BAR-B is used, which adapts the pressure from the provided six bar to the desired value. For the door operation and the milling head, two solenoid valves VUVG-L10-P53E-T-M5-1P3 are used. The jaw and vacuum gripper are operated via solenoid valves of the industrial robot. The vacuum gripper is actuated by a vacuum generator controlled by the PLC. All of the valves are 5/3-way valves.

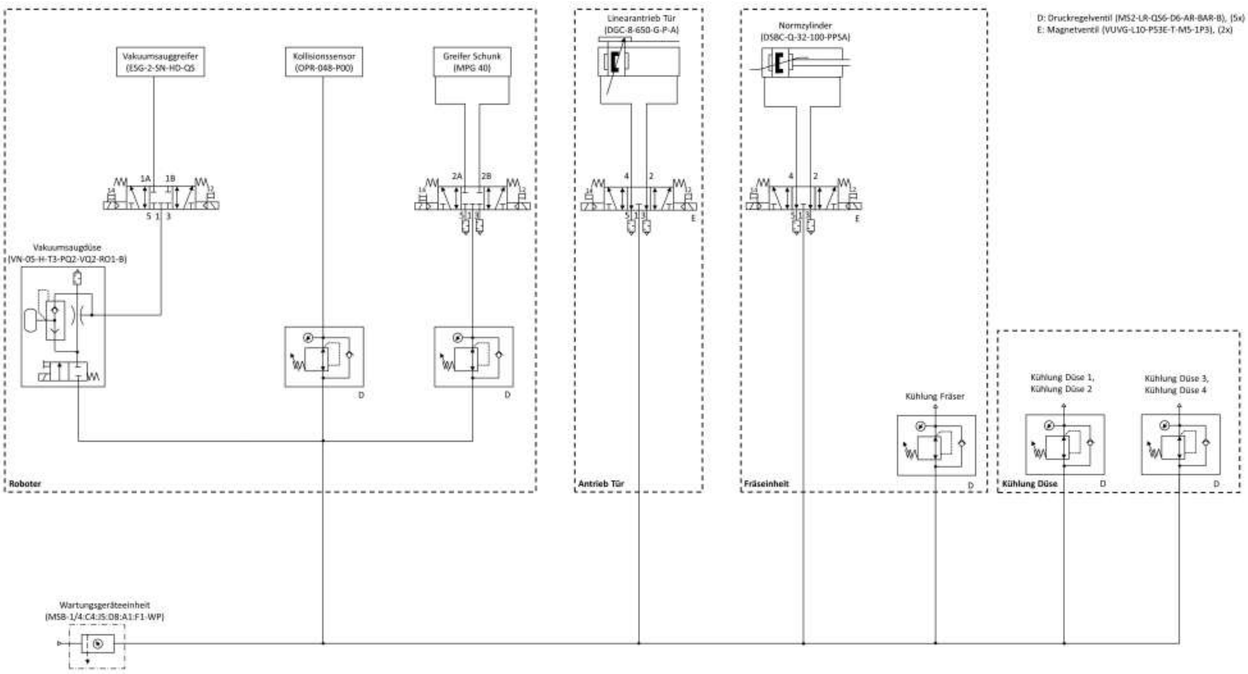


Figure 3.11: Pneumatic schematic of the 4K-FFF unit

3.5 Potential for Improvement

Recent literature shows that research in the field of function-integrated parts is currently of high interest. However, the investigated processes mostly do not use the full capability of the technology. The papers from Coronel et al. (2017), Ankenbrand, Eiche & Franke (2019), and Wasserfall (2015) show an automated process with no need for human interaction, but they lack a subtractive manufacturing process step that could improve quality and accuracy. Espalin et al. (2014) show a process that includes subtractive manufacturing, but manual integration of components is necessary. Nevertheless, the papers mentioned show the potential of function integrating parts. From the discussed papers, it can be learned that milling can improve part quality and is recommended (Espalin et al. (2014)). Furthermore, the production of function-integrated parts is possible on low-cost machines (Wasserfall (2015)). Pauses in the printing process can influence the result. Therefore cleaning procedures for the nozzle are recommended (Ankenbrand, Eiche & Franke (2019)).

Most of the mentioned papers use conductive ink or paste, whereas the 4K-FFF unit uses conductive filament. Research by Flowers et al. (2017) shows that conductive filament is a viable solution. Layer height, trace spacing, extrusion rate, nozzle temperature and heat bed temperature are critical parameters for the quality of the result (Barši Palmić, Slavič & Boltežar (2020)).

As mentioned above, the 4K-FFF unit can perform subtractive manufacturing and produce function-integrated parts. The only human interaction necessary at this point is the installation of threaded inserts used to improve contacting and join parts. This thesis aims to eliminate the need for human interaction during the process. Therefore a tool for an industrial robot is to be developed that is capable of grabbing and installing threaded inserts. In addition, a quick change system is implemented to allow tool changes of the robot, which enables the robot to change tools mid-process automatically. This allows for the usage of more than one effector in an installation procedure without human interaction. Both additions to the system can increase the degree of automation of the 4K-FFF unit.

4 Individual approach

This chapter covers all newly added features to the 4K-FFF unit, primarily the development and integration of a tool for an industrial robot that is capable of grabbing and installing threaded inserts. Later the implementation of a quick change system for the industrial robot is introduced.

4.1 End-Effector Development according to VDI 2221

The VDI 2221 described in chapter 2.4 provides a well-defined procedure that supports and structures the development process. This avoids errors and supports an iterative development process in which each step can be repeated until a satisfactory result is generated. It is therefore used to support the development process. Each step of VDI2221 is performed in the development process of the end-effector and is explained in the following section.

4.1.1 Clarifying and Itemising the Problem or Task

The first step in creating a list of requirements is understanding the existing process. Therefore the manual installation process is analysed. Resulting from this, a process chain according to VDI 2860 is created. Figure 4.1 shows the process chain. In the manual process, the insert is stored disorganised. It is clamped, normally by hand, but clamping with tweezers is also possible. Afterwards, the insert is oriented and positioned in the intended cavity of the component. The clamping is released. With the heat source, another fine positioning is done that corrects minor tilting errors. Lastly, the insert is joined with the part by applying pressure on the insert.

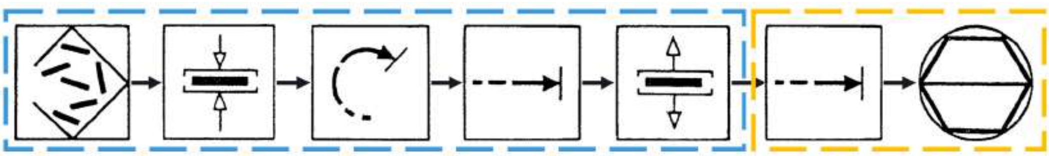


Figure 4.1: Process chain manual process

By analysing the manual process and examining the literature, influencing factors on the automated process are derived. The factors are illustrated in an Ishikawa diagram in figure

4.2. The component influences the process by the number of inserts that have to be installed and by their intended angle in relation to the print bed. The material choice influences the required operating temperature, while the accuracy of the cavity determines if a milling step needs to be performed before the installation (Gibson et al. (2021)). Accuracy of the cavity means the difference between the specification given by the inserts manufacturer and the actual hole size of the part. Pull-out force and torque-out strength are strongly influenced by the chosen insert and its knurl pattern (Pencom (2014)). The knurl pattern, diameter and length influence the insert's gripping, while the symmetry affects the orientation on the passive module.

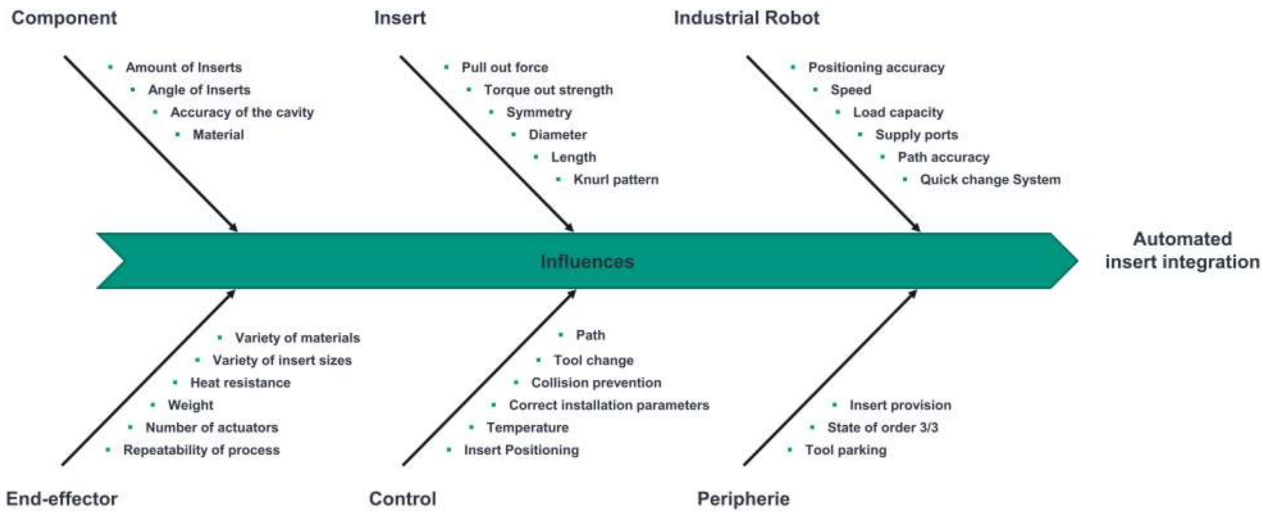


Figure 4.2: Ishikawa diagram with influences on automated process

Characteristics of the industrial robot are explained in chapter 2.2.3. The maximum speed affects the cycle times, accuracy affects the quality of the installation process, as precise installation depth, correct placement and the inserts angle in the cavity influence pull out and torque out strength (Pencom (2014)). The quick change system influences connectivity with ports for pneumatic or electric supply and determines whether manual engagement is required to attach the end-effector to the robot's mounting flange. The industrial robots' load capacity restricts the end-effector's maximum weight, whereas the actual weight of the end-effector influences inertia and gravitational forces on the industrial robot. The design of the end-effector affects the variety of materials that can be processed and the sizes of the inserts that can be used. Furthermore, it affects the structure's heat resistance and the process's repeatability. The number of actuators and electrical components affects the complexity of control of the end-effector. The control itself influences the process. It is responsible for correct positioning. The locations of the cavities need to be received from the STL file to receive accurate data. The control determines temperature surveillance and tool changes. The correct installation parameters, like depth, must be specified in the control code. Since a housing encloses the additive manufacturing unit, the control must ensure that the robot does not collide with the housing or any other object in its surrounding. Tool parking and insert provision are made on the passive module. It also determines the state of order of the inserts. In order to limit the degrees of freedom, the state of order of the insert must be restricted to 3/3.

Table 4.1: Requirements for end-effector development

Number	**Type**	**Requirement**
		Process
1	F	Usage of Industrial Robot
2	F	Inserts installable perpendicular to print bed
3	W	Inserts installable in various angles to print bed
4	W	Various insert sizes installable in one part (M3 - M6)
5	F	Heat source temperature adjustable
6	F	Repeatable process
7	F	Correct installation depth
8	F	Correct positioning
		Design
9	W	Inserts in magazine
10	F	Heat resistance of relevant parts
11	C	Actuators pneumatic or electric
12	W	Light and compact design
13	W	Robust design
14	W	Preferably usage of purchased parts
		Control
15	F	Control by HybridPlaner
16	W	Simple controls
17	C	Heat source permanently active or or only when joining

From these influences on the automated process, requirements for the end-effector are derived, which are collected in table 4.1. The requirements are divided into fixed, wish and choice requirements. Fixed requirements need to be fulfilled, wish requirements should preferably be fulfilled. With choice requirements, one of the solutions has to be selected. The fixed requirements for the process are the usage of the industrial robot, the possibility to

install inserts perpendicular to the print bed and an adjustable temperature of the heat source. Furthermore, a repeatable process with correct positioning and installation depth is required. The installation in various angles to the print bed and various insert sizes in one part are defined as wish requirements for the process. The insert sizes that should be processable are M3 to M6.
For the design, the inserts should preferably be stored in a magazine. Furthermore, the design should be light and compact but also robust. Purchased parts are preferred over manufactured parts to reduce the production time. Relevant parts have to be resistant to heat. This includes resistance to melting, damage due to expansion and shrinkage, or part failures due to jamming. Lastly, a selection has to be made if pneumatic, electric or both actuator types shall be used.
The control needs to be compatible with the HybridPlaner and should be as simple as possible. It is to be decided if the heat source should be permanently activated during operation, which could reduce preheating time but cause problems due to heat expansion, or if the heat source is only active during the joining process.

4.1.2 Determination of Functions and their Structures

The functions of the end-effector are fixation of the insert during transport, heating it up, releasing the fixation and melting it in. The fixation also needs to provide a centring method that ensures the placement of the insert in the TCP. Before the development, it was decided that the inserts should be stored on the passive module, not on the effector itself. Positioning is done by the industrial robot, whose positioning accuracy strongly impacts the quality of the process. A process sequence is necessary to install the insert. At first, the end-effector is moved to the insert's location, which is to be installed. Orientation and location need to be defined and known by the control unit. The insert is then fixated in the effector by some holding device. After securing the insert, it is transported by the industrial robot to its target location. The insert needs to be heated by a heat source and is released from the fixation. It is then melted in with a movement that lies in the centre axis of the cylindrical cavity. After the installation is completed, the end-effector is removed.

4.1.3 Search for Solution Principles and their Structures

A morphological box with possible sub-solutions is created to support the development of solutions. A morphological box is a method for systematic combination. In this classification scheme, the subfunctions to be fulfilled are listed in the first row and the active principles found are listed in the designated row for each solution. By combining an active principle that fulfils a subfunction with an active principle for a neighbouring subfunction of a functional structure, a possible active structure is obtained. This results in an overall solution when the linking process is done for all subfunctions. Only those functional principles can be combined, which are compatible with each other (Pahl et al. (2007)).

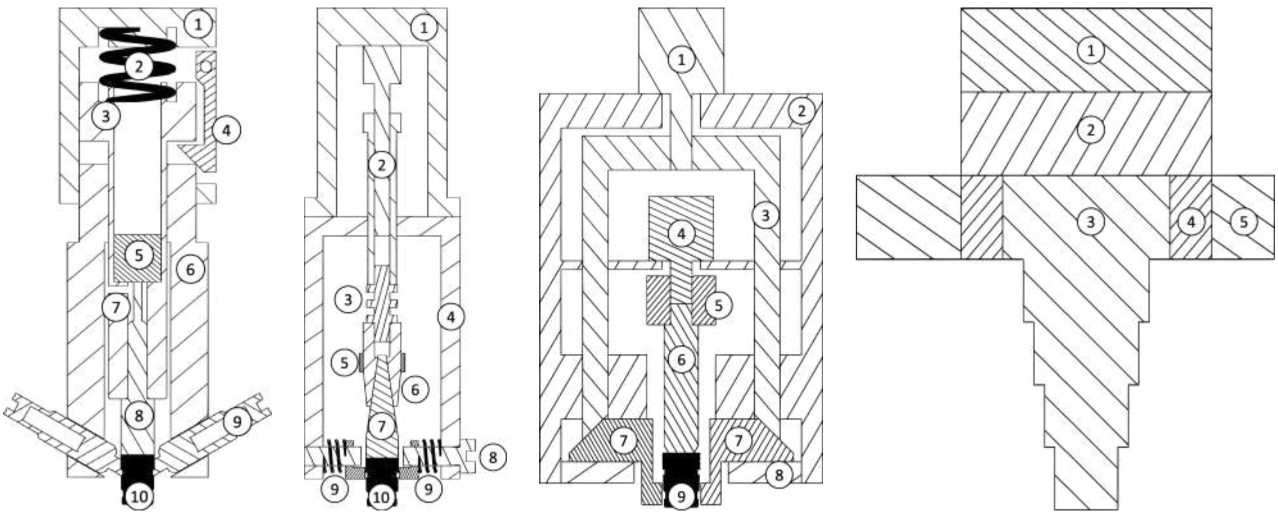
The subfunctions are defined in the previous chapter. The corresponding morphological box can be seen in table 4.2. Fixation can be achieved by a combination of magnet and spring. The inserts themselves are not magnetic. Therefore, a magnetic centring pin would be needed. The magnet could hold this pin, while a gripping mechanism holds the insert fixated on the centring pin. Alternatively, the thread of the insert could be used as a fixation device. It would simultaneously serve as a solution for centring. This would require a rotational device and resistance of the insert against rotation during pick up and after installation. Lastly, some gripping device that interacts with the inserts outside or inside could be used.
As mentioned, the centring can be done with a centring pin. This pin needs to be installed in the insert on the passive module. Each insert size needs an individual pin, while the mounting side must be universal for all sizes. A centring tip can be used for all inserts. It features a conical tip that fits all insert sizes. Whereas the centring pin secures against tilting, the centring tip only defines the position of the inserts opening. As mentioned above, the insert can be centred by using the thread as a fixation method. Lastly, a gripper can be used for centring.
The release can be done with an electric or pneumatic actuator or with a spring-loaded mechanism.
The industrial robot can be used to regulate the press-in depth. To prevent collision of effector and component, a part of the press-in device must extend beyond the effector. Alternatively, an electrical effector can be used to melt in the insert. The electrical effector needs a way to measure its travel to ensure the proper installation depth. Another way to ensure the correct depth is the use of a mechanical stop. This can be either in the form of a contact point that gives feedback when touching the component or a stop in the effector.
The heat source can either be a temperature adjustable soldering iron or a 3D printing hotend.

Table 4.2: Morphological box for end-effector development

Main-function	Solution 1	Solution 2	Solution 3	Solution 4
Fixation	Magnet	Thread	Gripping on the inside	Gripping on the outside
Centering	Centering pin	Centering tip	Thread	Gripper
Release	Pneumatic	Electric	Spring	
Definition of press-in depth	Industrial Robot	Electric actuator	Mechanical stop	
Heats source	Soldering Iron	3D printing hotend		

The combination of these possible solutions leads to four concepts, which can be seen in figure 4.3. The first concept is shown in (a). This concept aims to use the least possible amount of actuators to reduce cost and to simplify controls. It combines magnet and gripping as fixation method, a centring pin for centring, a spring-loaded release, a mechanical stop for the insert depth and a 3D printing hotend as heat source. The design consists of an upper (1) and lower (6) housing. In the upper part, a piston (3) is guided. A heat source is attached to the lower part of the piston. When the piston is pushed into the housing, a spring (2) is pre-loaded, and the piston is locked with a restraining hook (4). The insert (10) is transported on the centring pin (8). During transport, the pin is held by a magnet (5) inside the piston. Pressurised air can be applied through the hole (7) to eject the centring pin. The insert is held in place on the centring pin by spring plungers (9). The installation process runs as follows: The insert is stored on the passive module with a centring pin preinstalled. With the help of the industrial robot, the end-effector is lowered over the pin so that it slides into the intake of the piston, where it is held in place by the magnet. The magnet is located in an area where high temperatures can occur and therefore needs to be heat resistant. By lowering the robot, the spring plungers are pushed aside. The effector is lowered until the spring is loaded and the restraining hook is locked. After that, the insert is ready for transport. It is heated during transport. The insert is placed over the cavity when the target location is reached. After the target temperature is reached, the restraining hook is detached. This can be either done by an electric or pneumatic actuator. As a result, the spring presses the insert into the cavity until it reaches the mechanical stop, the lower part of the housing. An adapted centring pin for each size can offer the correct press-in depth for all sizes. After the installation process is complete, the effector is moved over a collection basin, where the pin is ejected with pressurised air. The pin can be reused in future installation processes.

Concept two is shown in figure 4.3 (b). It combines gripping on the outside, a centring pin, an electric release, a press-in depth regulated by an electrical actuator and a 3D printing hotend as heat source. An upper (1) and lower (4) housing support the construction. A captive linear actuator (2) is used. The insert (10) is centred with a centring pin (7). The pin is conically shaped to fit the intake (6). A heat source (5) in the form of a 3D printing hotend is attached to the intake. The intake is connected to the linear actuator with a heat sink (3) that prevents overheating of the motor. The centring pin and insert are clamped with two spring-loaded grippers (9), which are guided on a linear guide (8). The process starts with the centring pin preinstalled in the insert. In the beginning, the gripping jaws are closed with a small gap between them. Before the pickup, the electric motor positions the height of the intake of the centring pin so that after the pickup, the insert is in contact with the gripper jaws. To take in the insert and centring pin, the effector is lowered by the industrial robot. Thereby the centring pin enters into the gap between the jaws and presses them aside due to its conical form until it reaches the intake. The gripper jaws hold the centring pin and insert in place via spring force. After transport to the target cavity and heating of the insert to the target temperature, the insert is installed by lowering the linear actuator until the correct installation depth is reached. The centring pin is still held in place by the gripper jaws that now have contact with the pin. The effector is moved to a collection basin to eject the centring pin. The ejection is done by lowering the linear actuator until the gripper jaws have contact with the conical-shaped surface of the pin. It slips into the collection basin and can be reused during upcoming installation processes.



(a) (b) (c) (d)

Figure 4.3: Concepts for end-effector development

Concept three can be seen in figure 4.3 (c). The fixation is done by gripping on the outside, the centring is provided by a combination of a centring tip and gripper jaws. It features a combination of a spring-loaded mechanism and pneumatic release. The press-in depth is regulated with an electric actuator, while a 3D printing hotend is used as heat source. The design is assembled from a housing (2) and a bottom plate (8). A pneumatic piston (1) drives the gripper jaws (7) via a wedged diversion (3). A spring underneath the jaws is pre-loaded by activating the pneumatic piston, which is later used to reset them. The housing provides guiding for the wedged diversion. A linear actuator (4) moves the centring tip (6) together with the 3D printing hotend (5), which connects the two. The gripper jaws fixate the insert (9). At the beginning of the process, the insert is stored on the passive module. The end-effector is moved over the insert and is lowered until the insert touches the centring pin, which serves as a limit stop. The gripping jaws are closed with the pneumatic piston and fixate the insert. After that, the insert is transported to the target cavity and placed into it. The hotend heats the insert to the target temperature. Once the temperature is reached, the gripping jaws are opened by releasing the pressure in the pneumatic piston. The pre-loaded spring then opens the gripping jaws. The insert is pressed into the cavity with the linear actuator, which simultaneously melts the insert in. Lastly the tool is removed.

The schematic of concept four is shown in figure 4.3 (d). In this concept, a thread is used as fixation and centring method. The release is done with an electrical actuator, while the press-in depth is regulated with the industrial robot, and the heat is applied with a 3D printing hotend. This concept was inspired by two of the designs mentioned in the state of the art in chapter 3.3.3. Like in these concepts, the core of this design is a rotary motor (1), which is the mounting point for other components. The heated area is separated from the motor with a heat sink (2) to prevent overheating of the motor. A shaft with stair structure (3) features threads in the sizes that need to be applied. Each step length combined with the previous ones cannot extend the length of the insert to prevent collision of effector and component. Therefore compact design is necessary. The heat source (5) is connected to the shaft via a bearing (4) to prevent rotation of the heat source. The insert is stored on the passive module at the start of the installation procedure. It needs to be secured against rotational movement. The effector is placed over the insert and is lowered until the threads of the insert and shaft touch. The rotary motor turns until the insert sits on the shaft. During the following transport to the cavity, the insert is heated. The insert is pressed into the cavity by the industrial robot. Before the rotary motor can turn again to release the insert and finish the installation, the material must cool and harden.

4.1.4 Assessing and selecting the Solution Concept

At first, the advantages and disadvantages of each concept are evaluated. An overview is given in table 4.3. The first concept shows a very simplistic design, which simplifies the control. Only housing, restraining hook, piston and centring pins would need to be manufactured individually. The concept is compact and offers ideal centring by using centring pins. A disadvantage is the uncontrolled and rapid release caused by the spring. Furthermore, the spring plungers feature a spherical contact point with the insert, which is not ideal for gripping. Due to heat expansion, the guiding of the piston could clamp. In addition, the centring pin could get stuck in the piston. Because of the passive gripping device, there has to be contact between the spring plungers and the inserts during the heating phase, which could lead to clamping or damage of the spring plungers. Lastly, the centring pins have to be ejected, which necessitates an additional process step.
Concept two features one actuator, which simplifies the controls. The usage of centring pins offers ideal centring. A shoulder screw could be used to simplify the gripping jaws' guidance. Due to the linear motor, the press-in method can be selected. Press-in can be performed either by using the industrial robot or the linear motor, depending on which method offers better accuracy. Problems due to heat expansion could occur, although a heat break is included. The heat break should prevent heat creep into the motor, but the permanent contact between the gripper jaw and insert can lead to heating the of guide and jamming of the jaws. Additionally, the centring pins must be ejected at the end of the process.
In the third concept, the press-in depth can be controlled either by the installed linear motor or by the industrial robot. The actively controlled gripper jaws prevent heat transfer between the jaw and the insert, as there is no contact during the heating phase. The design is robust and potentially offers high process reliability. However, two actuators are used, which complicates control and increases costs. A centring tip is used for centring, potentially having a worse performance than a centring pin. The assembly consists of many individual parts that have to be manufactured.
With the fourth concept, many of the necessary parts can be purchased. The thread ensures ideal centring during the process. It is a compact design that requires only one actuator, which keeps the control simple. The main problem with this concept is that the molten material around the insert must solidify before the end effector can be removed. Otherwise, the insert may be twisted out of the cavity. This leads to waiting times and slower process cycles. To pick up the inserts, they must be provided on the passive module so that they are secured against rotation to allow them to be screwed in. Due to the limited length of the individual threaded parts, the threaded part that is effective in the insert is short, potentially leading to

problems. In addition, heat must be supplied by a bearing to allow rotation. The bearing must be heat resistant, otherwise jamming can occur.

Table 4.3: Advantages and disadvantages of concepts

Concept	Advantages	Disadvantages
1	- Simple design - Lots of purchasable parts - Compact - Ideal centering	- Uncontrolled ejection with spring - Contact point of gripping device spherical - Possible problems due to heat expansion - Centering pins have to be ejected - Passive gripping jaws
2	- One actuator - Ideal centering - Simple guiding of gripping jaws - Press-in can be executed by robot or linear motor	- Possible problems due to heat expansion - Centering pins have to be ejected - Passive gripping jaws
3	- Press-in can be executed by robot or linear motor - Actively controlled gripping jaws - Robust design	- Two actuators - Centering tip - Lots of individual parts
4	- Lots of purchasable parts - Ideal centering - Compact - One actuator	- Cooling needed before before tool removal - Inserts need to be secured against rotation on passive module - Short threaded sections for each insert - Heat transfer through bearing

After evaluating the advantages and disadvantages, one of the concepts has to be chosen for further development. Therefore a benefit analysis is carried out. Following Pahl et al. (2007) a target system is defined to determine the weighting factors of the benefit analysis. The weighting is carried out in stages to balance factors of sub-goals against an upper-level goal. Figure 4.4 shows the target system. The values given on the left side of each box are the weighting factors in the sub-category. All left values of one sub-category need to add up to one. The right value is the weighting factor multiplied by all upper-level weighting factors.

The overall goal is to develop a functioning concept. Therefore manufacturing, control, design and process reliability are defined as sub-goals. Manufacturing, control and design are evaluated as equally important. Process reliability is weighted as the most crucial factor for a functioning concept. In the manufacturing category, a minimum of workshop parts and a minimum overall design price is equally weighted. Only a control system as simple as possible is requested for the control category. The design should be robust but also light and compact. In the process reliability category, the most critical sub-category is reliable transport because losing the insert during transport would lead to failure of the process. Minor problems with centring or heat creep could be tolerated, but these are also essential features. Tool removal is important, as errors in the removal process could lead to pull-out of the insert while the material is still soft, which would lead to process failure. Minor errors in the press-in depth do not fail the process but can lead to worse insert performance concerning pull-out strength and torque resistance.

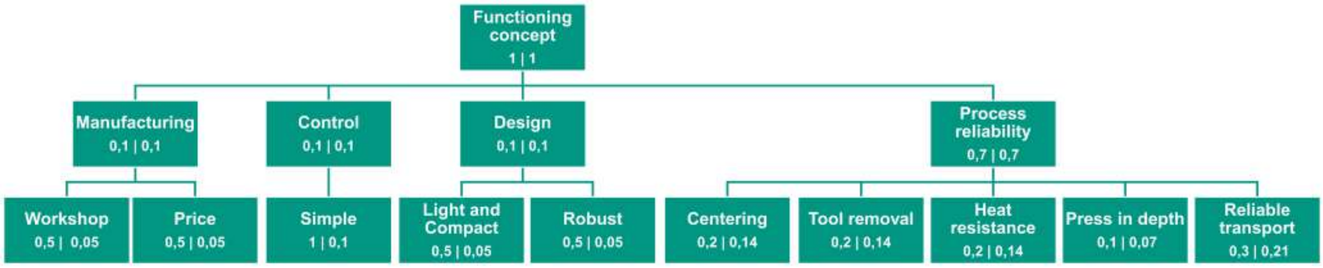


Figure 4.4: Target system for benefit analysis

Table 4.4 shows the result of the benefit analysis. The abbreviation Wt. stands for weight, Wtv. stands for weighted value. Pahl et al. (2007) give reference points for the rating, where 10 is given for an ideal solution, 7 for a good solution, 4 for an adequate solution and 2 for a weak solution. Values in between can be used. Concerning manufacturing, concept 4 needs the least manufacturing effort, followed by concept 1, which still has a good rating. Concepts 2 and 3 require more effort and therefore are rated lower. Concepts that need fewer actuators need less expensive parts and are therefore rated higher. Furthermore, the control is simplified when fewer actuators are used. Concept 4 is the lightest and most compact concept, followed by 1 and 2. Concept 3 is not as compact and therefore rated the lowest. All of the concepts can be seen as equally robust, except for concept 4, which is more delicate because of the threaded part, which cannot exceed predefined diameters. A centring tip and thread can be seen as an ideal centring method, whereas the combination of gripping and a centring tip still offers a good solution. Concept 1 has significant issues with heat resistance. The same goes for concept 2, but with a lower impact on the overall performance. Both other concepts have built-in measures against heat creep and are therefore rated with good values. For concept 1, the press-in depth is regulated with a mechanical stop, but a spring-loaded mechanism pushes the insert rapidly and uncontrollably, leading to a low rating. Concept

4 does not offer flexibility in the press-in method, unlike concepts 2 and 3 and is therefore rated lower. Because of passive gripping devices and possible problems with this system, concepts 1 and 2 are rated lower than the others. Overall, concept 4 features the potentially most reliable transport method, although problems can occur due to the lack of thread length. Active gripping is a proven method and therefore rated with a good value.

The benefit analysis shows the highest potential in concept 3, which is therefore chosen for further development.

Table 4.4: Benefit analysis

Rating criteria			Concept 1		Concept 2		Concept 3		Concept 4	
Nr.	Description	Wt.	Value	Wtv.	Value	Wtv.	Value	Wtv.	Value	Wtv.
1	Manufacturing	0,05	8	0,4	6	0,3	5	0,25	10	0,5
2	Price	0,05	9	0,45	8	0,4	5	0,25	7	0,35
3	Simple control	0,1	10	1	8	0,8	6	0,6	8	0,8
4	Light and compact	0,05	8	0,4	8	0,4	6	0,3	9	0,45
5	Robust	0.05	8	0,4	8	0,4	8	0,4	6	0,3
6	Centering	0,14	10	1,4	10	1,4	7	0,98	10	1,4
7	Tool removal	0,14	6	0,84	6	0,84	9	1,26	3	0,42
8	Heat resistance	0,14	2	0,28	4	0,56	8	1,12	8	1,12
9	Press-in depth	0,07	5	0,35	8	0,56	8	0,56	6	0,42
10	Reliable transport	0,21	5	1,05	5	1,05	8	1,68	6	1,26
	Sum	1		6,57		6,71		7,4		7,02

4.1.5 Subdivision into Modules, Interface Definition

The subdivision can be seen in figure 4.5. The three primary functions of the construction are a gripping device (1), a press-in unit (2) and a heating device (3). The gripping device consists of a pneumatic cylinder and a wedge diversion, redirecting the pneumatic force by 90 degrees. The gripping jaws need to be guided and spring-loaded for resetting them into the start position after the release of the gripping force. Therefore a spring with the correct dimension and spring force is to be selected. A fitting pneumatic cylinder and wedge system need to be chosen.
A linear motor and a guiding system are needed for the press-in unit. Furthermore, a reference

switch that can provide position data for the linear motor needs to be selected. The centring tip needs to be designed to prevent clamping of the tip in the insert.
The heating device needs a way to produce heat, measure the temperature and control it.

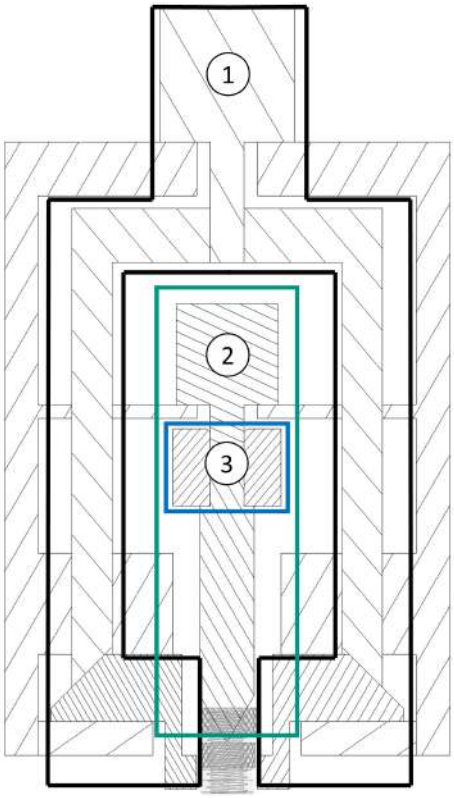


Figure 4.5: Subdivision of modules

4.1.6 Designing the Modules

In the following design of the gripping module, the heating device and the press-in unit are described in detail.

4.1.6.1 Gripping Module

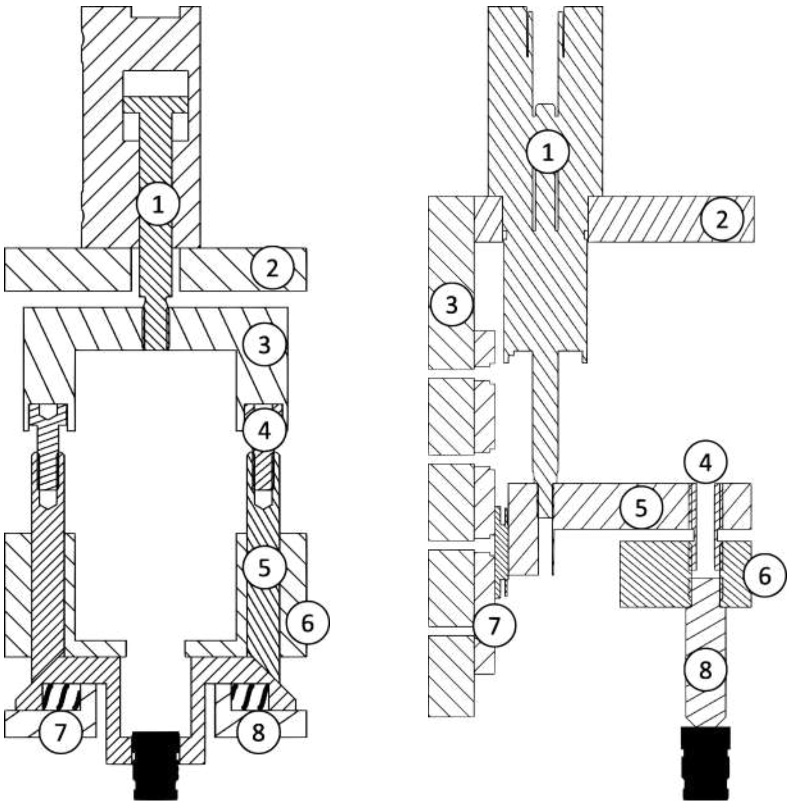
At the start of the design process, the shape of the gripping jaws is decided. An opening angle of 120 degrees is the optimum, as smaller values lead to contact of the two jaws when gripping small inserts. On the other hand, larger opening angles lead to contact points close to each other when gripping a round object with a large diameter. This can lead to instability and tilting during transport. The next step is the design of the cavity for the spring. The jaws should be as short as possible to reach a compact design. With this requirement, a cavity with a length of 9 mm with open jaws and a length of 4.4 mm with closed jaws is designed. Height and width are fixed values that can be adapted to fit a spring with correct length dimensions. A fitting spring with an outer diameter of 4.9 mm and a maximum spring force of 10 N is selected. The cavities' width and height are adapted to the diameter of the spring to prevent tilting or turning of the spring.

A pneumatic cylinder needs to be selected to actuate the gripping device. Since one of the design requirements is a light and compact design, the cylinder should be as small and lightweight as possible. At first, the minimal travel of the cylinder is determined. The largest insert that needs to be handled is of the size M6 and has an outer diameter of 8.7 mm. The outer diameter specifies the necessary distance the jaws are required to travel. Because of the wedge mechanism, only half of the travel is needed, as a movement of the cylinder moves two gripping jaws by the same travel. The jaws need to open further than the insert size during the grabbing process. One millimetre on each side is chosen as security against contact. Therefore a cylinder with a travel of 5.35 mm is sufficient to fulfil the requirements. The next bigger available size is a cylinder with 10 mm travel, so this size is chosen. Another aspect to consider is the required gripping force. The force is calculated using a formula derived from Hesse (2011). The gripping force is dependent on the mass m of the gripping object, the gravitational constant g, the maximum acceleration in gravitational direction a_z, the bisected opening angle of the gripping jaws α, the friction coefficient μ between jaw and gripping object and a security factor S.

$$F_G = m(a_z + g)\frac{sin(\alpha)}{2\mu}S \tag{4.1}$$

For the material pairing of aluminium and brass, no friction coefficient could be found in the technical literature. Therefore a relatively low value of 0.1 was used for security reasons. The angle α is 60 degrees, as the opening angle is divided by two. For the value a_z, an equivalent of $2.5g$ is used, as this is given as a brake acceleration during emergency shutdown by Hesse (2011). The security factor was chosen as two, and the mass of the insert is three grams. With this, a minimum gripping force of 0.9 N is necessary. In addition to this force, the spring forces of the reset springs need to be overcome. The selected springs have a maximum spring force of 10 N. Therefore, the force that needs to be produced by the pneumatic cylinder has to be greater than 20.9 N. The smallest available cylinder has a diameter of 12 mm. With a maximum working pressure of six bar, this cylinder can produce a force of 68 N, which is sufficient for the application.

After the selection of the purchased parts, the wedge diversion can be designed. As seen in figure 4.6 (a), the pneumatic cylinder (1) is fixed to a ground plate (2). The force is distributed by a U-shaped part (3). Via a pair of screws (4) used for fine adjustment of the jaw opening, the force is guided onto the wedges (5), angled at 45 degrees. The wedges are held in a guide (6), which in turn is connected to the base plate via a side plate which does not lay in the visual layer of the figure. The rear sides of the gripper jaws (7) are angled at 45 degrees, allowing the force flow to be diverted. The reset springs have a stopping point at the rear of the jaw and a contact point with the base plate (8). This allows the jaws to be reset by spring force. The base plate is fixed to the guide. The guide of the wedges also guides the jaws from above and laterally. From below, the gripper jaws are guided by the base plate.



(a) (b)

Figure 4.6: Design of the modules

A calculation is carried out to ensure that a 45 degree angle is a reasonable choice for the wedge diversion. The concern is that the spring force is insufficient to overcome the friction forces that act on the wedge system. This would lead to a self-locking mechanism and system failure, as the jaws could not be reset. Therefore the forces that act on the wedge system are analysed. The right gripping jaw, that can be seen in figure 4.6, is simplified in figure

4.7 (a). The acting forces are the gravitational forces G_1 and G_2 on each wedge, the normal forces F_{N1} and F_{N2} and the frictional forces F_{F1} and F_{F2}. The calculation is carried out to determine which force F_1 is needed to reset the wedges into the start position. Figure 4.7 (b) shows the reaction forces between the wedges and the just mentioned forces. The contact force F_C acts perpendicular to the contact surface, the frictional force in the contact F_{FC} acts perpendicular to the contact force. Both forces are split into their X and Y components. Figure 4.7 (c) shows the second wedge with the corresponding forces in the opposite direction.

After solving the equations in X and Y direction for F_1, the boundary conditions are applied. G_1 equals 57 mN, while G_2 equals 102 mN. The friction coefficients are derived from Verein deutscher Ingenieure (2015). The coefficient for aluminium on aluminium in lubricated conditions is 0.12. Steel on aluminium has a coefficient of friction of 0.18. Both angles α and β are 45 degrees. With these values, F_1 is calculated to be 0.22 N. With the pretension of the spring of 1 mm, active during all states of operation, and a spring rate of 1.8 N/mm, the pre-load is sufficient in every scenario to ensure a trouble-free procedure.

A formula from Krause (2004) is used to validate the calculation. This formula only considers cases with the same friction coefficients, which is not the case for the problem on hand. Both calculations provide the same results while using the same friction coefficient. Therefore the calculation is considered correct.

4.1.6.2 Heating Device

As the end-effector is used in an environment with 3D printing equipment, using a 3D printing hotend is a solution that is easy to include in the system. Therefore an aluminium heater block, a thermistor cartridge and a heater cartridge of the V6 hotend by the company E3D are used.

4.1.6.3 Press-in Unit

The core part of the press-in unit is a linear actuator. A linear motor with included linear guide is used to prevent the turning of attached parts. The required travel is determined by the height of the largest insert, which has a length of 12.7 mm. The motor should have a minimum stroke of 16 mm to guarantee sufficient travel. A motor close to this value is needed

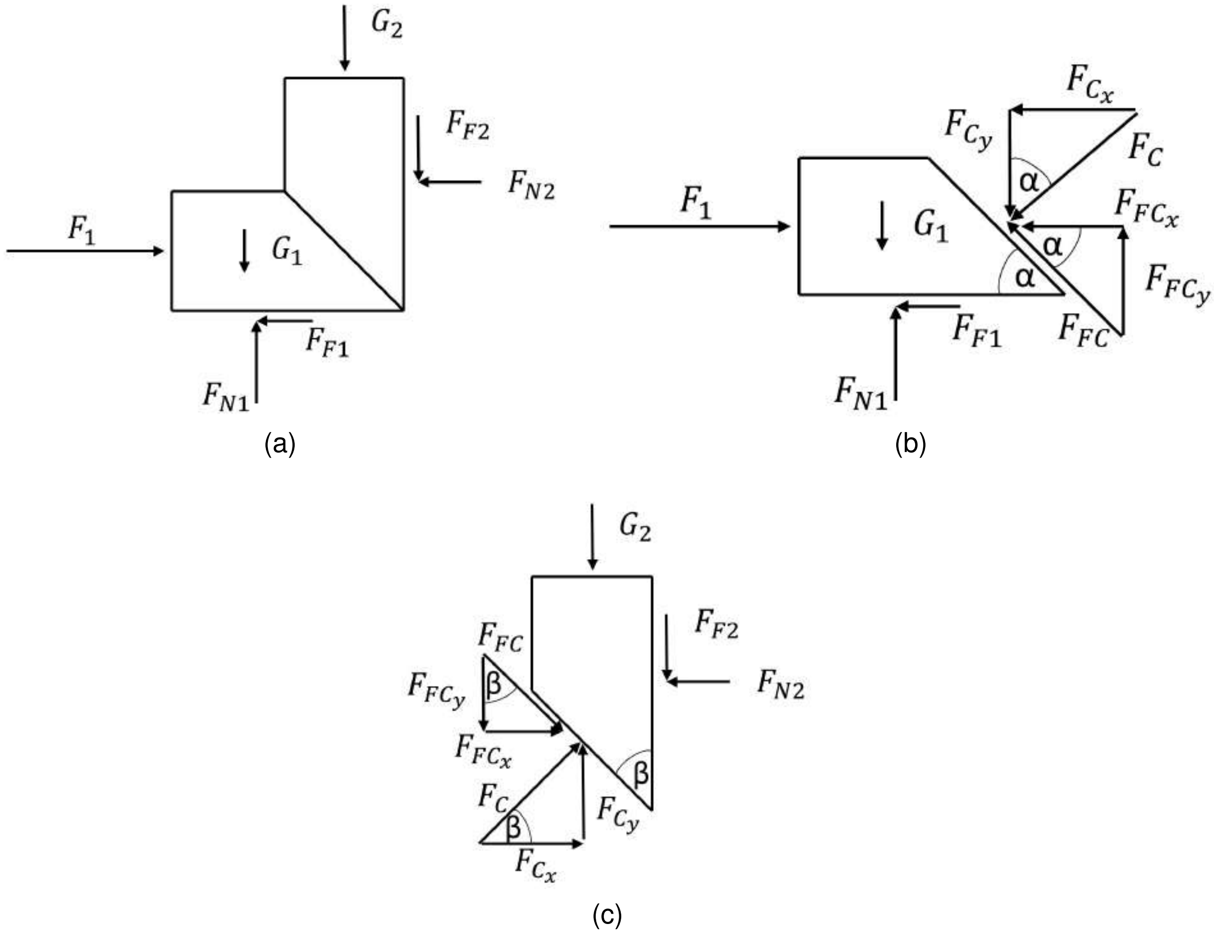


Figure 4.7: Forces acting on wedge mechanism

to keep the end effector compact. The cheapest available motor with a built-in linear guide has a travel of 19.1 mm, so this motor is chosen for the press-in unit.

Figure 4.6 (b) shows the design of the press-in unit. A linear motor with a built-in guide (1) sits on a ground plate (2). The ground plate is connected to a side wall (3). To add additional support against tilting of the press-in system, an auxiliary linear guide (7) is used. The linear guide consists of a carrier and a rail. It is supported by a two-row recirculation ball bearing guide. The guide carries a connecting element (5), which is connected to the motor and a heat break (4). The guide ensures that twisting and tilting of the connecting element is prevented, as the thread of the linear motor is insufficient to guarantee correct guidance. A mechanical switch that touches the connecting element is included as a reference point for the motor. The heat break prevents heat creep into the connecting element and the motor. Heat break and centring tip (8) are connected by an aluminium block (6). The centring tip is the element that needs to be hot in order to melt in the insert. It is therefore made out of copper for better heat conduction. The heat break is made of steel, which is a worse heat conductor than aluminium and copper. All other parts are made from aluminium for a lightweight design.

A concern of the design is that clamping could occur between the centring tip and the insert, as a conical-shaped tip is used. This could lead to a pull-out of the insert while removing the tool with the material not thoroughly cooled. Depending on the parameters, a self-locking design is possible. This would mean a force is necessary to separate the insert and centring tip. A tapered connection is a similar application, for which calculation procedures exist. Therefore, a calculation is carried out, following Haberhauer (2018). Equation 4.2 shows that the opening angle α of the centring tip, the friction coefficient μ between the tip and insert and the press-in force $F_{PressIn}$ have an impact on the release force.

$$F_{Release} = F_{PressIn} \frac{sin(\frac{\alpha}{2}) - \mu\, cos(\frac{\alpha}{2})}{sin(\frac{\alpha}{2}) + \mu\, cos(\frac{\alpha}{2})} \tag{4.2}$$

The maximum force produced by the linear motor is 46 N. Data about friction coefficients of copper on brass could not be found in the technical literature. According to Wittel, Spura & Jannasch (2021), the pairing of cast iron and copper alloys like brass has a friction coefficient of 0.25, and copper on copper can have a friction coefficient up to 1. Therefore 0.25 is used as a reference, and values up to 1 are considered in the design. Figure 4.8 shows the required release force over the tip angle of the centring tip. Positive force values mean that the mechanism is not self-locking, and no release force is required. Negative values mean that a release force is necessary. Planned angles for the centring tip are 60 degrees and 90 degrees. Therefore the limits of the friction coefficient are calculated. It can be seen in figure 4.8 that a friction value of 0.55 is acceptable for a tip angle of 60 degrees, and a combination of a friction value of 0.99 and a tip angle of 90 degrees is acceptable. A tip with 60 degree angle is preferred, as it can prevent contact of tip and gripping jaws. On the other hand, a tip with 90 degree angle prevents clamping of the tip with a high probability. As a result, both of the tip angles will be manufactured and tested.

Furthermore, the forces acting on the linear guide must be calculated. The forces and torques that arise in the worst case due to maximum acceleration during braking and with simultaneous gravitational loading result in loads of less than 0,005 Nm for all cases with a mass of the suspended part of 30 grams. When melting in, loads with a maximum force of 46N and a lever arm of 6.5mm result in 0.3 Nm of torque. Since the minimum tolerable dynamic torques of the guide are 0.8 Nm, the guide is designed to be safe in all cases.

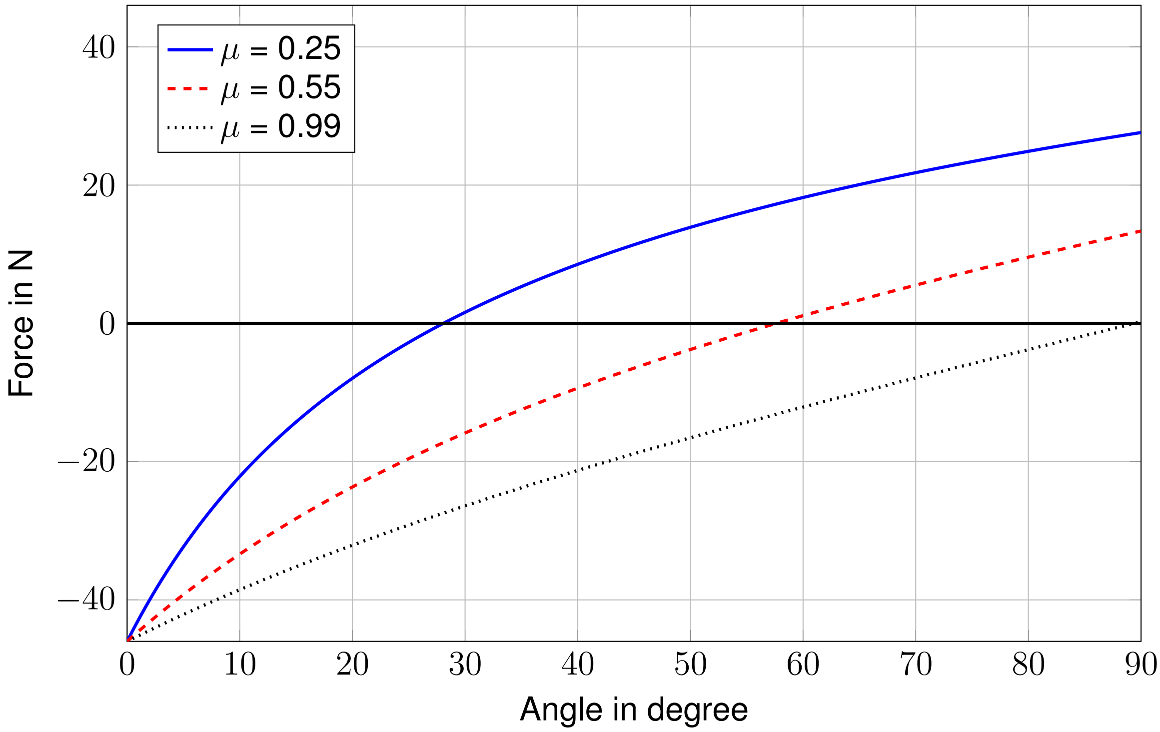
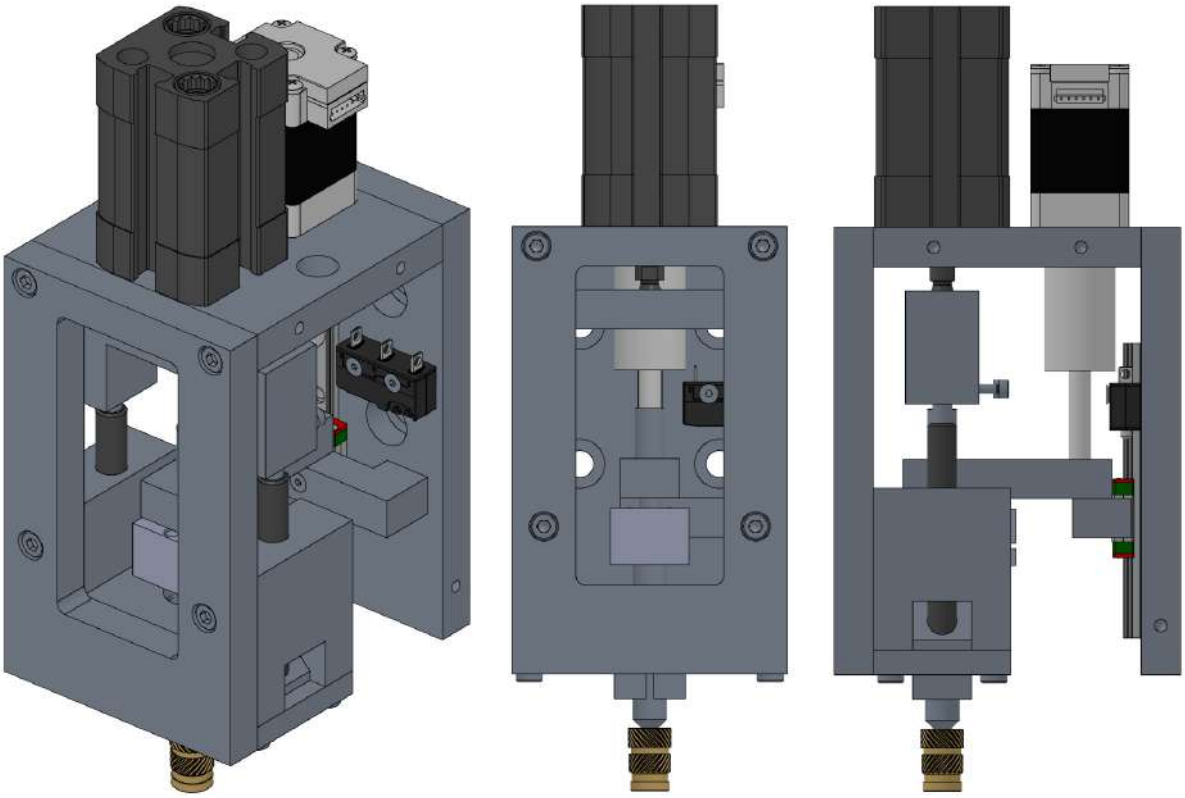


Figure 4.8: Release force depended on tip angle for different friction coefficients

4.1.7 Integration of Product as a Whole

Figure 4.9 shows the integrated system with all components. Both actuators are fixed to the same ground plate. The pneumatic cylinder is located on the left, and the linear motor is on the right side. The selected pneumatic cylinder is the model "ADN-12-10-A-P-A" by Festo, the linear motor is the model "LGA201S06-B-TDBA-019" by nanotec. As the plane of gripping and press-in needs to be the same, the connecting element achieves a coincide gripping and press-in point. The aluminium block mentioned in the previous chapter 4.1.6.3 is replaced by an aluminium heater block which holds the thermistor and heater cartridge. The selected hot end is the V6 hotend from E3D. While the front plate holds the guide of the gripping jaws and the wedge, the back plate is used to fixate the linear guide and the reference switch. As a reference switch, a micro switch "ZF Mikroschalter DB2C-A1AA" is selected, the linear guide is the model "MGN05C" produced by Hiwin. In the isometric view in (a), the reference switch with contact point on the connecting element can be seen. The back plate also attaches the assembly to the industrial robot.



(a) (b) (c)

Figure 4.9: Integration of sub-systems to final assembly

4.1.8 Elaborating the Details of Execution and Use

In this step, the technical drawings are derived from the CAD models. The drawings can be found in the appendix from A1 to A11. The fits are designed according to recommendations of Gomeringer et al. (2014) for sliding guides. All fits for the gripper jaws are designed as H7/f7. As the metal pins for the wedges are purchased parts and fitted with m6, another fit is required here. With a pairing of E8/m6, a similar playing fit as H7/f7 is achieved. Therefore this fit is selected. All parts are equipped with holes for centring pins to ensure exact fit when assembling. All fits for the centring pins are a pairing of H7/m6 following recommendations of Hoischen & Fitz (2014). Surface quality for relevant parts of the guide is designed to provide smooth gliding and to fit the manufacturing capabilities of the in-house machines.

The last section of VDI 2221, assurance of the fulfilment of the requirements, will be discussed in the results chapter.

4.2 Quick Change System

In addition to the development of the end-effector, a quick change system is selected and installed for the 4K-FFF unit. The system needs to allow automated tool changes. Compatibility with all existing tools and connectivity with the 4K-FFF unit and its control are requirements for the system. Furthermore, a low price and expandability are required in case another effector needs to be added. Lastly, a design that fits the passive module needs to be selected. Two separate steps need to be considered for the selection. First, the quick-change system must be selected and then the storage system.

Schunk offers various sizes of quick change systems. The smallest and cheapest system does not have enough carrying capacity and does not support the existing tools. Therefore the second smallest system, "SWS 005", is chosen. It does fit the existing tools and is the cheapest viable option. The system's connectivity needs to be considered in addition to the quick change system itself. An anti-collision and overload protection sensor is used that has one pneumatic connection and a three-pin electrical connection. The jaw gripper has two pneumatic connections, the vacuum gripper has one pneumatic connection. Two pneumatic connections and eleven electric connections are used for the newly developed end-effector. Therefore all pneumatic activated tools could be operated at their individual pressures if six pneumatic feed-throughs are available. In addition, a minimum of 14 electrical feed-throughs are required. An electrical feed-through module with 30 pins is selected to allow the expansion of the system. The selected quick change system offers six pneumatic feed-throughs, which is sufficient for the existing tools. Under normal circumstances, the anti-collision sensor does not need feed-through, as it is attached to the robot's flange and therefore is not part of the component that can be decoupled. Two actuators could operate at the same pressure if another effector is added to the system. The selected quick change system is therefore classified as suited.

Four types of storage racks are available in general. Only two of those are compatible with the selected quick change system. The others are fitting for different quick change system sizes. Compatible are the pin & bushing and the pin & rack system. As the pin & rack system has fixed suspension points for the tools and can only handle three effectors, it is not suited for the application. The pin & bushing system is modularly expandable, and the suspension points can be chosen individually. It can support all effectors and fits onto the passive module. It consists of a storage module that is attached to a vertical profile. The corresponding intermediate plate fits exactly into the storage module and makes contact at

Figure 4.10: Quick change system components (Schunk (2022))

three points the ensure exact placement. The tools are fixed to the intermediate plate and can therefore be stored in the rack. A proximity switch can be added to the storage module. With the switch, the presence of tools can be detected as a safety measure. The chosen rack is the "SWM-S pin & bushing". Figure 4.10 shows the components of the rack. The stationary part consists of an attachment bracket (2), a vertical (3) and horizontal (4) profile and storage modules (5). Additionally, inductive proximity switches (9) can be used as a safety feature. The intermediate plate (6) is connected to the quick change adapter and the tool. The correct size of the intermediate plate for the "SWS 005" is pictured on the left of figure 4.10.

As mentioned above, it is planned to use the collision sensor directly at the flange to protect all effectors against crashes. The collision sensor can tilt in small margins due to torque loads. The maximum tilting to be expected is calculated. A maximum torque of 5 Nm can occur during the installation process. According to the sensor's datasheet, this torque can lead to a tilt of 0,6 degrees. This could cause a displacement of 1.7 mm at the press-in point. Forces up to 25 N are not critical and do not lead to any displacement. Due to this possible problem, another tool configuration is prepared to be equipped for the possible problem. In this configuration, the newly developed end-effector is operated without collision protection.

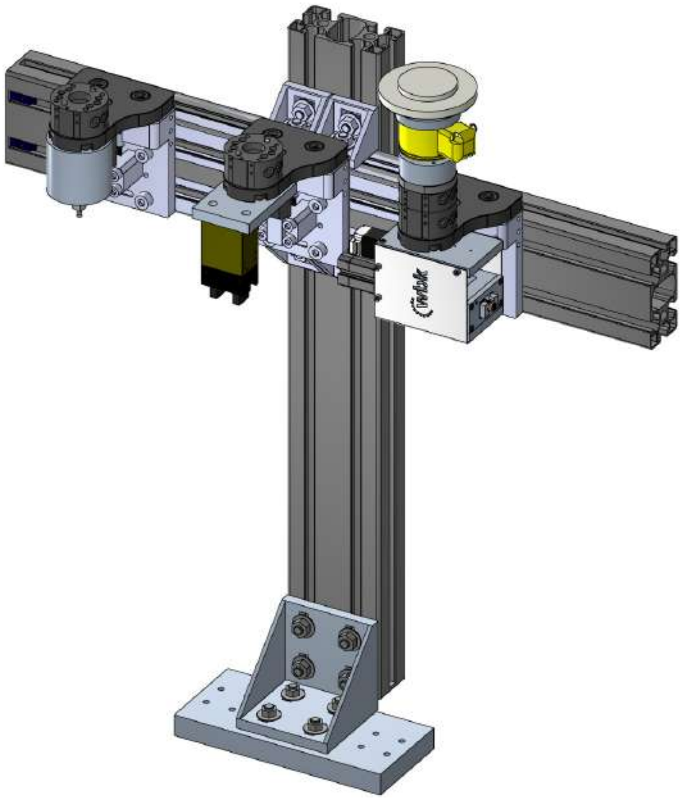


Figure 4.11: Quick change system

The collision sensor is operated with only one of the other two tools, a jaw gripper or vacuum gripper. Thus, the tilting caused by the collision sensor can be prevented.

Figure 4.11 shows the first configuration of the quick change system with a storage rack. On the right side, the newly developed end-effector can be seen. Attached is the quick change system, the collision sensor and the flange of the industrial robot. The jaw gripper can be seen in the middle and the vacuum gripper on the left. An adapter plate is needed to fit the holes in the module to attach the foot of the rack to the passive module. Additionally, adapter plates are needed to connect the existing tools to the intermediate plate. Another two adapter plates are needed for the second configuration. All drawings of the adapter plates can be found in the appendix from B1 to B6.

5 Results

The first part of this chapter covers the implementation of the quick change system. It enables automated tool changes of the robot and must therefore be implemented, before other effectors can be used. Later, the effector's implementation in the existing hardware and software structure is explained. Lastly, an experimental trial that tests the invention's capabilities is described.

5.1 Implementation of Quick Change System

Due to cost considerations, the quick change system features two storage modules instead of the three needed for all tools of the industrial robot. The structure is therefore designed in a way that a further storage unit can be added in the future. This would require another quick-change adapter, a storage module, an intermediate plate, and an inductive proximity sensor. The rack is mounted on the passive module, so it takes up as little space as possible, which is required to provide inserts. It is therefore mounted on the rear edge. Since the holder does not fit on the storage module, an additional adapter plate, "adapter plate passive module", must be used. The drawing of the adapter plate can be found in appendix B1. The mounting on the industrial robot is done with a collision sensor. To connect the sensor to the quick change head, the adapter plate "adapter plate quick change system" is used, which can be found in appendix B5.

For each location of the storage modules, a program for the industrial robot is written to get and bring back the tools. The exact coordinates of the two storage modules are given in appendix C.2. An exemplary code is shown in the appendix in listing C.1. The procedure starts with the robot traversing a point to prevent collision with the housing of the FFF unit. It is then positioned close to the quick change system. Before the pick-up, a position above the final location is reached, after which a linear movement is performed. The last point before the pick-up is 20 mm higher in z-Direction than the pick-up point. All point data is given in the base coordinate system. Outputs 1 and 2 actuate the first valve included in the robot. In the pick-up process, output 2 is set to false to ensure the quick change system can be closed. Output 1 is then set to true to close the quick change system. For the return process, the order of the output actuation is reversed. After the pick-up, the tool is moved to a default position above the passive module. Details on the pneumatic connection of the quick change system are explained in the following section.

5.2 Hardware Integration of End-Effector

The end-effector is assembled according to the CAD model. Due to minor inaccuracies in the manufacturing process, the heating tip and the jaws do not align perfectly. Therefore spacer plates are added between the linear guide to compensate for the alignment error. As explained in the previous chapter, the end-effector features a pneumatic cylinder, a linear motor (M), a thermistor (TH), a heating cartridge (H) and a reference switch (R), which need to be connected to the control unit of the system. The electrical wiring is done by three cables, one power cable (P) with four cores, one signal cable (S) with 12 cores and one cable for the linear motor (E) with four cores. Motor and signal cables are shielded to prevent interference. The power cable has a larger wire diameter to support the higher current needed for the heating cartridge. All connections are made using the power feed-through module of the quick-change system. The pin layout of the quick change system with the colour of the corresponding cables can be seen in figure 5.1. The motor is connected via the pins b, W, R and L. Heating cartridge and thermistor are connected via pins d, Y, T and N. The reference switch uses the pins f, a and V. The motor is connected to the control unit using the EtherCAT Terminal EL7037.

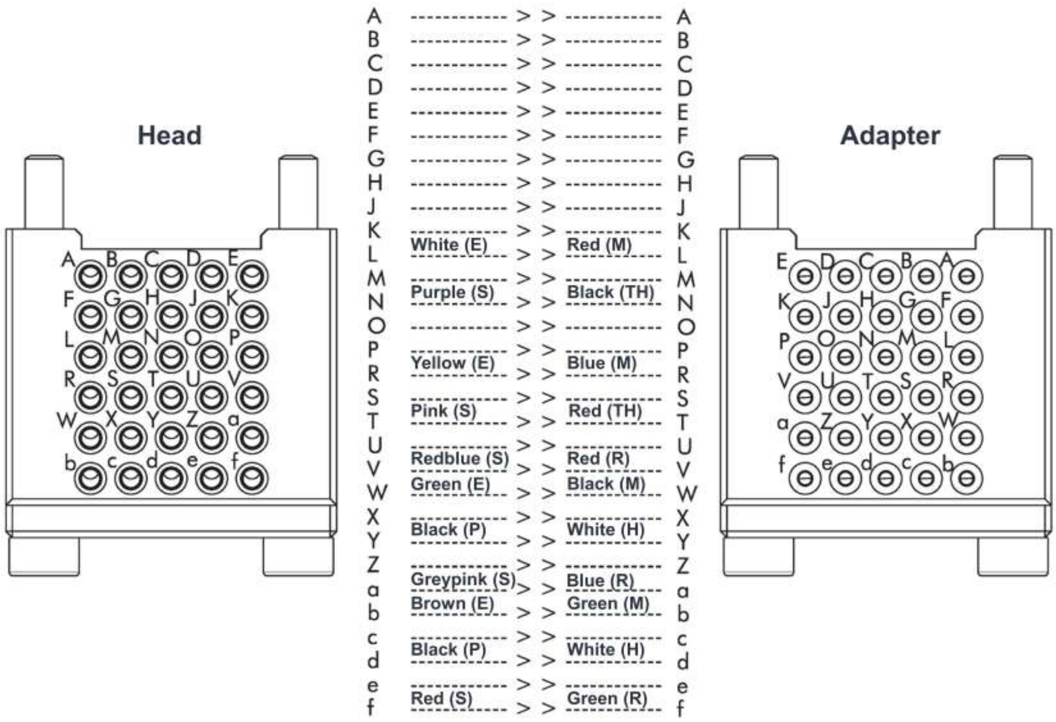


Figure 5.1: Electric connection of end-effector

In chapter 3.4.4 the pneumatic schematic of the 4K-FFF unit is explained. The pneumatic system needs to be extended to integrate the quick change system and the end-effector. The quick-change head is another pneumatic element that must be controlled by a pressure valve. In the previous version of the pneumatic system, only one of the two valves of the robot was used, the formerly unused valve can be used to control the quick-change head. Figure 5.2 shows the updated pneumatic schematic. The effectors are no longer permanently connected to the pneumatic system but can be optionally connected via a quick coupling. By applying pressure to feed-through one, the compact cylinder of the effector and the jaw gripper can be opened. They can be closed by applying pressure to feed-through two. As in the previous version, the effectors are controlled via one of the valves integrated into the robot. Both valves are connected to an air outlet "R". The circuit diagram shows that the quick-change head, jaw gripper and compact cylinder are all supplied with the same pressure since the two valves of the robot are fed via a single supply line. If this causes problems, another valve must be integrated in the future, which is controlled separately by the PLC, like the valves for the door and milling unit. The vacuum gripper is connected to the vacuum generator via feed-through three. The overload sensor is supplied with compressed air through the "AIR 2" line of the robot. It is connected directly to the service unit via a pressure regulating valve and is permanently under pressure. Changes are only made in the section of the robot. The pneumatics of the door, milling unit and cooling nozzles remain unchanged.

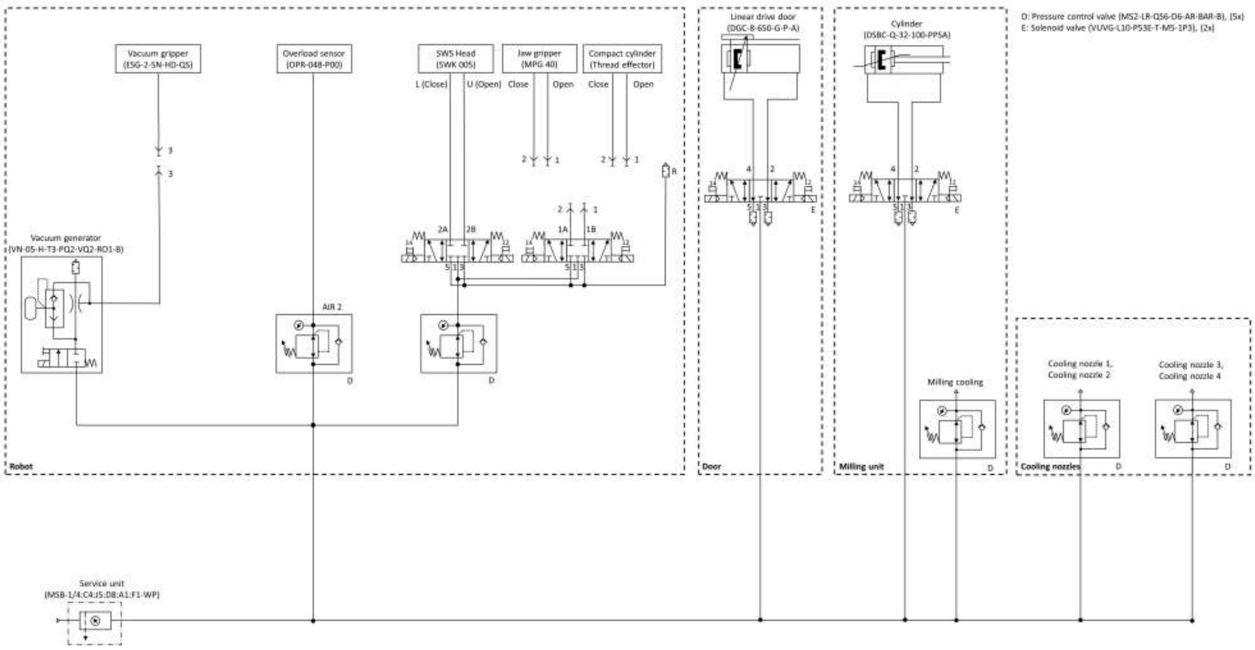


Figure 5.2: Extended pneumatic schematic

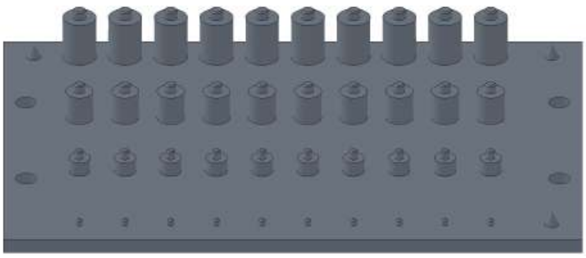
An energy chain is used for the robot cable routing, which is newly installed. Due to the new cables and their guidance, the robot's structure is slightly larger. Since the space was already tight before the change and the robot could only just enter the printing chamber, collision with the printer's housing cannot be prevented after the installation. For this reason, an outer plate of the housing has been removed. The removal allows the robot to enter the build area without any problems. During the current state of work (August 2022), the intended heaters for the printing area of the printer are not in operation, so the part of the housing is not needed. The housing needs to be closed again for future use of the heaters. A larger door or an additional axis for the robot could solve the issue with access to the printing chamber.

5.3 Software Integration of End-Effector

In order to be able to use effectors within the robot program, the TCP for each effector has to be measured. This can be determined via a standard KUKA routine. For this purpose, an XYZ 4-point measurement method is used for each effector. During the XYZ 4-point method, a measurement point, which serves as the reference point of the measurement, is approached from four different positions. Using the four different measurement points and the associated flange positions, the robot controller calculates the coordinates of the TCP with respect to the flange coordinate system. After the measurement is completed, an error value is calculated that expresses the quality of the measurement. The specified measurement error should be below a value of 0.5 mm. Measurements with a larger error should be discarded and rerun. In addition to measuring the TCP's position, the tool's load data must be determined and passed to the robot control. The load data is relevant because it is considered in the calculation of the paths and accelerations of the robot. In addition, correct load data is important for the KUKA-internal load data check. The robot control provides monitoring during operation to determine whether an underload or overload is present. Depending on the configuration, a warning message is issued when an underload or overload is detected or the robot is stopped. The load data consists of mass, the position of the centre of gravity (COG) in the reference system, the orientation of the main inertia axes (MIA) and the individual mass inertias around the axes of the main axis system JX, JY and JZ. The CAD data is analysed for each effector to determine the load data. Therefore, all the effector components and the quick change systems components must be included in the CAD assembly. In order to be able to calculate the load data of the individual effectors, the correct mass properties have to be assigned to each component of the assembly. All load data can be determined by analysing the mass properties of the entire effector assembly. During this analysis, care has to be taken to ensure that all load data is determined relative to the robot's flange coordinate system. For this purpose, a new coordinate system has to be assigned correctly in the CAD model. Using this method, the thread-effector, vacuum, and jaw gripper are added to the robot's tool/base management menu. The data of the measurements and the load data for each effector can be found in appendix C.3, C.4 and C.5. Additionally, a measuring tip is added to fit into the vacuum gripper's mount. The measuring tip is used to measure base coordinate systems.

A shelf is designed and attached to the passive module to supply the inserts. Figure 5.3 (a) shows the shelf, (b) shows how it is mounted on the passive module, and the provision of the inserts. The robot approaches the shelf from the viewer's perspective. The stepped design of the shelf allows all insert sizes to be gripped without the robot colliding with the inserts. The cylindrical fixation of the inserts is 0.4 mm smaller than the inner diameter of the inserts to compensate for inaccuracies in the pick-up. If the effector does not position exactly over the inserts, the inserts will not tilt but will be pushed into the correct position and picked up straight. The conical pyramids in the corners of the shelf are used to measure the shelf coordinate system. The measurement of a base can be carried out using a KUKA-internal routine. For this purpose, the 3-point method is used. The measured base is saved in the tool/base management menu and can be edited later. Postprocessing is necessary in this case because the height of the conical pyramids is not taken into account during the measurement and must therefore be corrected afterwards. Measurement requires a measured tool, which is mounted on the flange of the robot. The measuring tip is used for this purpose. Three different points are approached during the 3-point method, the first being the origin of the base coordinate system. The second point defines the direction of the X-axis, and the third point defines the X-Y plane. For the storage shelf, the origin of the base is marked by the cone in the top right of figure 5.3, the X-Axis is marked by the cone in the bottom right corner, and the XY-plane is marked by the cone in the top left corner. The measurement is done in a reference coordinate system, in this case, the base coordinate system of the robot. With respect to this coordinate system, a transformation is calculated, uniquely defining the position of the shelf coordinate system. The transformation data consists of the position of the origin in X, Y and Z coordinates, as well as the orientation of the base coordinate system with the rotation angles A, B and C. With the known coordinates of the shelf, the positions of the inserts can easily be specified. The distance between the inserts of the same size is 15 mm each. This distance can be used to specify the position of all other inserts after the robot controller has the information about the position of the first insert. The base measurement of the storage rack can be found in appendix C.1.

For the control of the thread-effector, numerical control (NC) code is used. The NC control implements the control commands for the relative movement between the tool and the



(a)

(b)

Figure 5.3: Storage shelf for inserts

workpiece. Control commands are known as NC code. These path instructions are encoded by letters and numbers. The control code is usually created with the aid of computer aided manufacturing software and transmitted to the control system. Among other things, an NC code contains switching commands (M commands, T commands) that are transferred to the PLC. The geometry data (G commands) and technology data (drive, speed, other) are transferred to the interpolator. The interpolator calculates the command values for the drive of the axes from the transferred path instruction. The tool movement results from the superposition of the axes (Brecher & Weck (2021)).

The commands used to control the end-effector are as follows:

- **V.E.Insert.xPos = *X-Coordinate***: Transfers the X-Value of the inserts target location specified in *X-Coordinate* to the PLC.
- **V.E.Insert.yPos = *Y-Coordinate***:Transfers the Y-Value of the inserts target location specified in *Y-Coordinate* to the PLC.
- **V.E.Insert.zPos = *Z-Coordinate***:Transfers the Z-Value of the inserts target location specified in *Z-Coordinate* to the PLC.
- **M107**: Waits until the temperature specified in M108 is reached and then waits 10 seconds additionally to ensure that the insert reaches the target temperature.
- **M108 = *Temp***: Sets the target temperature of the heating element and uses a two-point controller to regulate the temperature of the heating element by comparing the value of the thermistor and the target value. *Temp* is to be replaced with the target temperature value.

- **M110 = *Insertnumber***: Transfers the requested insert number to the PLC.
- **M111**: Sets input 30 ("allclear") true and waits for robot output 20 ("startinsert") to be true.
- **M112**: Sets input 31 ("Insertdone") true and waits for robot output 21 ("robotclear") to be true.
- **G74 QH = 1**: References the thread-effectors linear motor by driving into the direction of the reference switch until it is reached.
- **G1 QH = *Location* F*Velocity***: Traverses the linear motor of the end-effector to the location specified in *Location* with the speed specified in *Velocity*. The maximum travel of the motor is 14.5 mm from the reference switch.

5.4 Procedure of the Installation Process

Figure 5.4 shows the schematic of the installation procedure for threaded inserts. At first, the printing process needs to be paused, and the print head needs to be moved to a location where collision with the robot's tool is prevented. Depending on whether the end-effector is already attached to the effector or stored on the quick change shelf, the robot must first pick up the correct tool. The robot then moves the effector from its default position to the requested insert on the insert storage shelf and places the jaws at a correct height above the insert. By activating the pneumatic cylinder, the insert is gripped. It is then moved to its target destination in the printing chamber. Care must be taken to avoid collision with housing and other objects. This is done by assigning points on the robot's path that must be traversed. Once the target is reached, the pneumatic opens the gripper jaws. Then the heating device is activated. The linear motor responsible for melting in the insert must be referenced using the reference switch since it does not have an integrated travel measurement. The next step is that the motor moves the heating tip until it makes contact with the insert to preheat it. Until the heating device reaches its target temperature, the process is paused. After that, the linear motor moves the heating tip to its final position, which causes the insert to be melted into its target cavity. Another waiting interval is required, as the effector is attached to an overload sensor with minimal play when exposed to force. This can lead to a tilting angle and, therefore may result in the insert sticking out a small distance after it has been installed. This can be prevented with the waiting interval, as the material further softens during the waiting

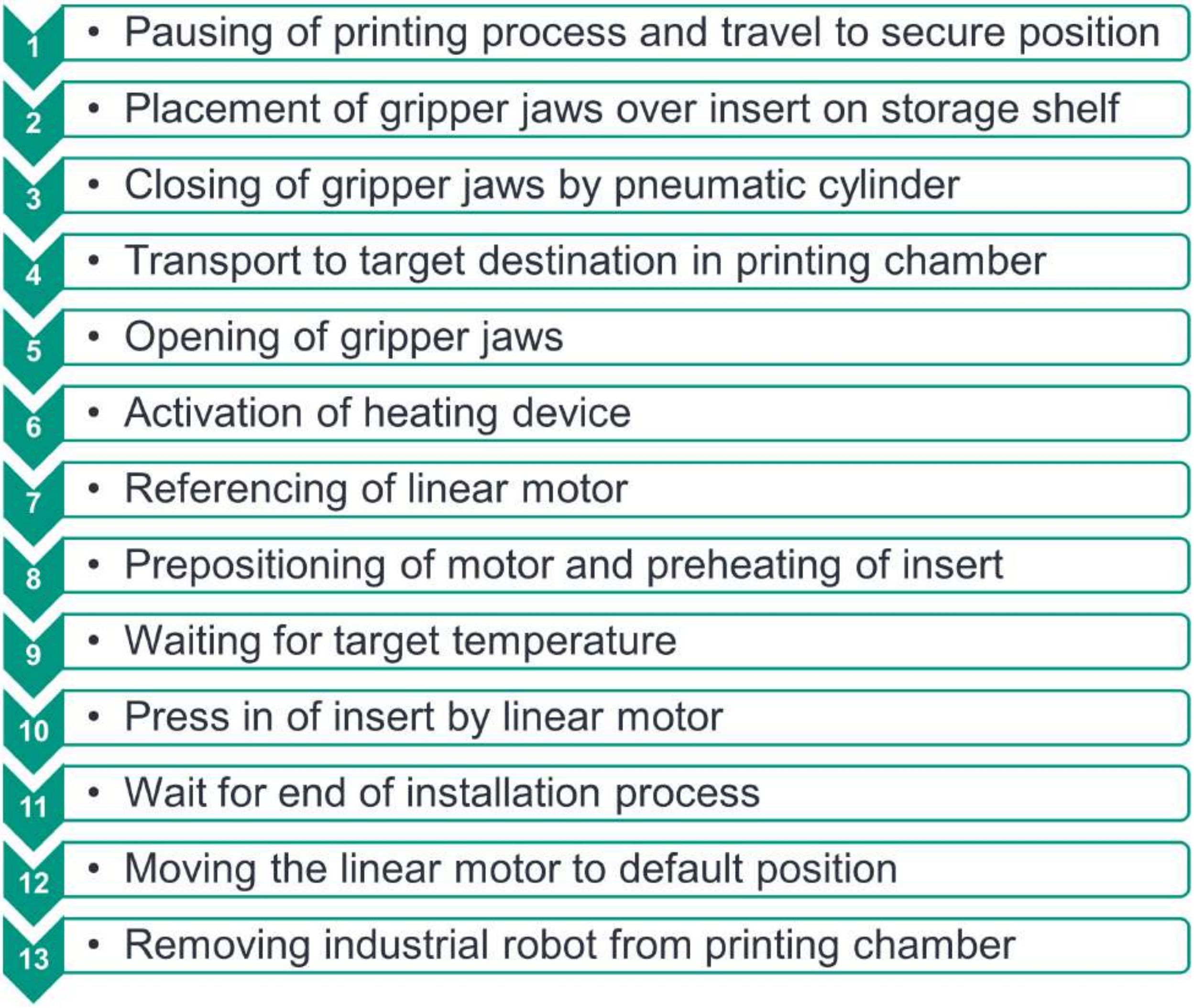


Figure 5.4: Installation procedure of threaded inserts

time and the force applied by the overload sensor is sufficient to press-in the insert entirely. After the installation is complete, the linear motor of the thread effector is moved to its default position. Lastly, the end effector is moved out of the printing chamber. Depending on whether further inserts are installed, the effector is returned to the quick-change storage shelf.

5.5 Experimental Trial

The newly developed tool must be tested for functionality. In addition, the ideal parameters for operation must be determined. A preliminary investigation is carried out in which the influence of hole diameter and temperature on the installing behaviour is examined. Afterwards, parameter optimisation is performed to determine operating parameters. Thereby, the optimum values for temperature, end position of the heating tip, pick-up position and waiting times are determined.

5.5.1 Preliminary Investigation

The preliminary investigation is carried out using a soldering iron with adjustable temperature. A linear guide is used to press in the inserts to which the soldering iron is attached. The investigation aims to determine how temperature and hole diameter affect the force required for installation. For this purpose, the workpiece is placed on a scale, the values of the scale during the installation process are recorded with a camera and evaluated after the process. This method is not very accurate because the scale has hysteresis and does not react directly to changes in the compressive force. However, since all measurements are carried out with the same measuring setup, the relative results are valid. By comparison it is possible to make a statement whether a parameter has a has a positive or negative effect on the process. The time-force curve resulting from the measurement is integrated over time to make the results comparable. This provides an impulse value for each measurement. For the insert sizes M4 and M5, 27 measurements each were performed. Three measurements each, in which the nominal diameter recommended by the manufacturer is adjusted in CAD by minus 0.2 mm, plus 0.1 mm and plus 0.3 mm. For each of these diameters, tests are performed at 180 ℃, 210 ℃ and 300 ℃, resulting in 9 cases per insert size. For each case, three samples are taken, and the average of the result is calculated. The samples are printed using an Ultimaker 2+. Figure 5.5 shows the analysis result. The blue bars show the values for M4, the green bars for M5. It can be seen that a higher temperature significantly lowers the force which is required to install an insert. A larger hole diameter has the same effect.

This result is not surprising since a higher temperature softens the material and makes it easier to displace, and a larger hole diameter means that less material has to be displaced. However, both parameters have a significant influence. Therefore the importance of the two parameters is emphasised. It can be concluded that care must be taken to ensure that the hole diameter matches the manufacturer's specifications as closely as possible. In addition, a high temperature is recommended for the installation. PLA is generally processed at 210 ℃. At 300 ℃ and higher values, the degradation of PLA begins (WANG & LI (2008)). Therefore, a compromise between high temperature and safety against degradation is chosen, and the operating temperature for the heating device is set to 250 ℃.

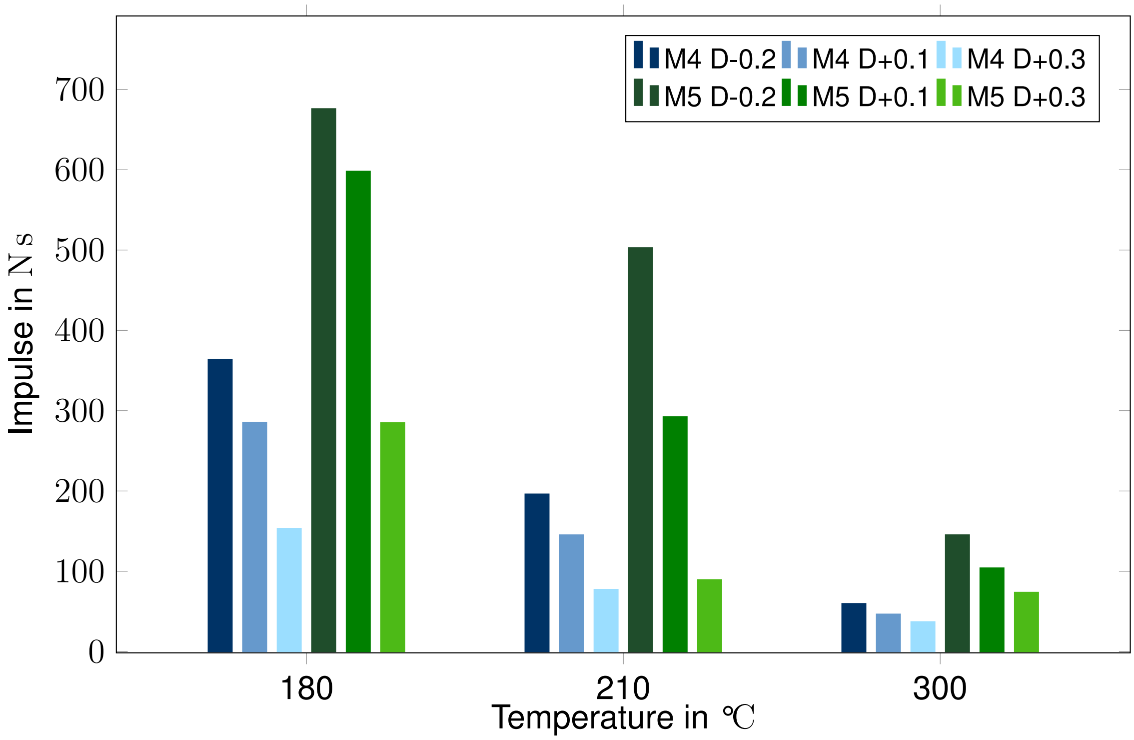
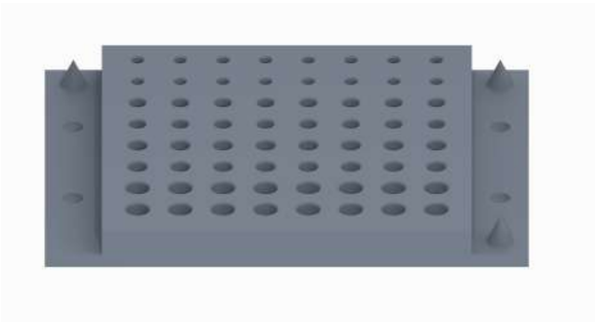


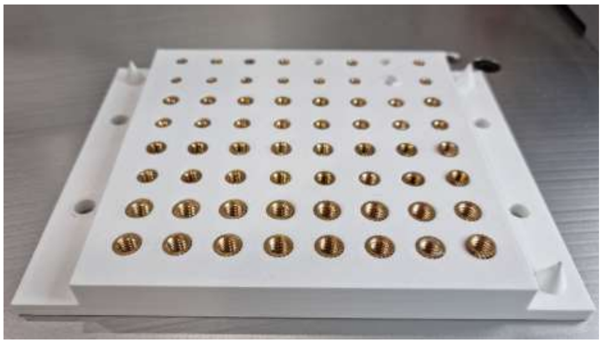
Figure 5.5: Impulse for different temperatures and hole diameters during installation process

5.5.2 Parameter Optimisation

In the first step after the installation, the positioning angels of the end-effector are measured manually to ensure the correct angle during pick-up and installation processes. The measurement is taken in the base coordinate system and then converted to the base of the print bed. The angle A is 90.97°, B -3.94° and C 89.79°. The ideal pick-up points for the inserts from the shelf were determined as part of the parameter optimisation. These must be known so that the insert's overhang downwards beyond the effector's jaws can be determined. The value of the overhang must be known to determine the required distance between the bottom of the tool and the top of the workpiece during installation. All inserts have a smaller diameter at the bottom than at the top. This allows the insert to be placed in the hole without requiring direct installation, as the insert is self-supporting. Ideally, the section of the insert with a narrower diameter is lowered into the hole. The second goal of parameter optimisation is to determine the ideal traverse points for the robot that fulfil this requirement. After that, the travel points of the linear motor must be determined. The effector's linear motor will approach two points for each insert. At the first point preheating of the insert is done, which requires contact between the heating tip and the insert, but no force is exerted. Additionally, a point is required at which the insert is located in its final position after the linear motor is traversed. It is advisable to determine the waiting times needed for the insert to reach the required temperature. Finally, the travel speeds of the linear motor influence the quality of the installation, therefore these are analysed as well.



(a)



(b)

Figure 5.6: Component for parameter optimisation

A custom component with 16 holes per insert is designed and manufactured for parameter optimisation with the Ultimaker 2+. This component is then attached to the passive module. The component is shown in Figure 5.6 (a). Like the insert shelf, it has conical pyramids, which makes it possible to measure a coordinate system for the component. The component's coordinate system can be found in appendix C.1 along with the data of the storage shelf's coordinate system. As a result of the newly assigned coordinate system, the coordinates for the installation can be taken directly from the CAD model. The parameters mentioned above for the end-effector operation were gradually determined by systematically adjusting them and comparing the installation results. The optimised parameters can be found in table 5.1. During the parameter optimisation, it was noticed that the contact point of the melting tip and the gripping point of the gripper does not correspond exactly. This can lead to the insert being slightly tilted after the installation. Therefore, a correction is made in which the effector moves a small margin after the insert has been placed, thereby placing the tip directly above the insert. The correction parameters are listed in table 5.1 and refer to the base coordinate system.

Table 5.1 shows the result of the optimisation. The pick-up height value indicates the distance between the bottom of the thread effector and the support surface on which the inserts are stored. Installation height is the distance between the bottom of the effector and the upper side of the hole in which the insert is placed. Preheat travel is the distance the linear motor travels from the reference point to make contact with the insert and preheat it. Final travel is the distance the linear motor moves from the reference point to install the insert entirely. The

Table 5.1: Results of the parameter optimisation

Pickup height M3 [mm]	Pickup height M4 [mm]	Pickup height M5 [mm]	Pickup height M6 [mm]
2.5	4.1	5.5	8.7
Installation height M3 [mm]	Installation height M4 [mm]	Installation height M5 [mm]	Installation height M6 [mm]
0.9	2.2	3.5	5.2
Preheat travel M3 [mm]	Preheat travel M4 [mm]	Preheat travel M5 [mm]	Preheat travel M6 [mm]
3.6	4.1	4.3	5.7
Final travel M3 [mm]	Final travel M4 [mm]	Final travel M5 [mm]	Final travel M6 [mm]
7	9.5	11.1	13.8
Installation temperature [℃]	Motor speed preheat [mm/min]	Motor speed final [mm/min]	Waiting time [s]
250	90	30	10
	Correction X [mm]	Correction Y [mm]	
	0.8	-0.3	

installation temperature is the temperature to which the insert is heated in the process. Motor speed preheat is the speed at which the motor moves from the reference point to the preheat point. The motor speed final is the speed at which the motor moves from the preheat point to its final position while simultaneously melting the insert in. Wait time is the time required to reach the target temperature of the melting tip and the insert after the target temperature has been reached at the thermistor. Due to the FFF process, holes in components are usually smaller than planned in CAD. It is therefore necessary to design the holes larger in the CAD. For the Ultimaker 2+ an oversize of 0.2 mm on the diameter is recommended, for the 4K-FFF unit a larger oversize is necessary. Here, the hole should be designed at least 0.6 mm larger. Alternatively, the milling module can be used to acquire the correct diameter size. In addition to the fact that the holes in the FFF process are smaller than planned in the CAD, there is often an overhang at the top of the holes, which further reduces the top diameter of the hole and can cause problems when placing the inserts. It is therefore recommended to include a chamfer of 0.5 mm at the top of the hole.

One of the concerns regarding the design during the development phase was overheating of

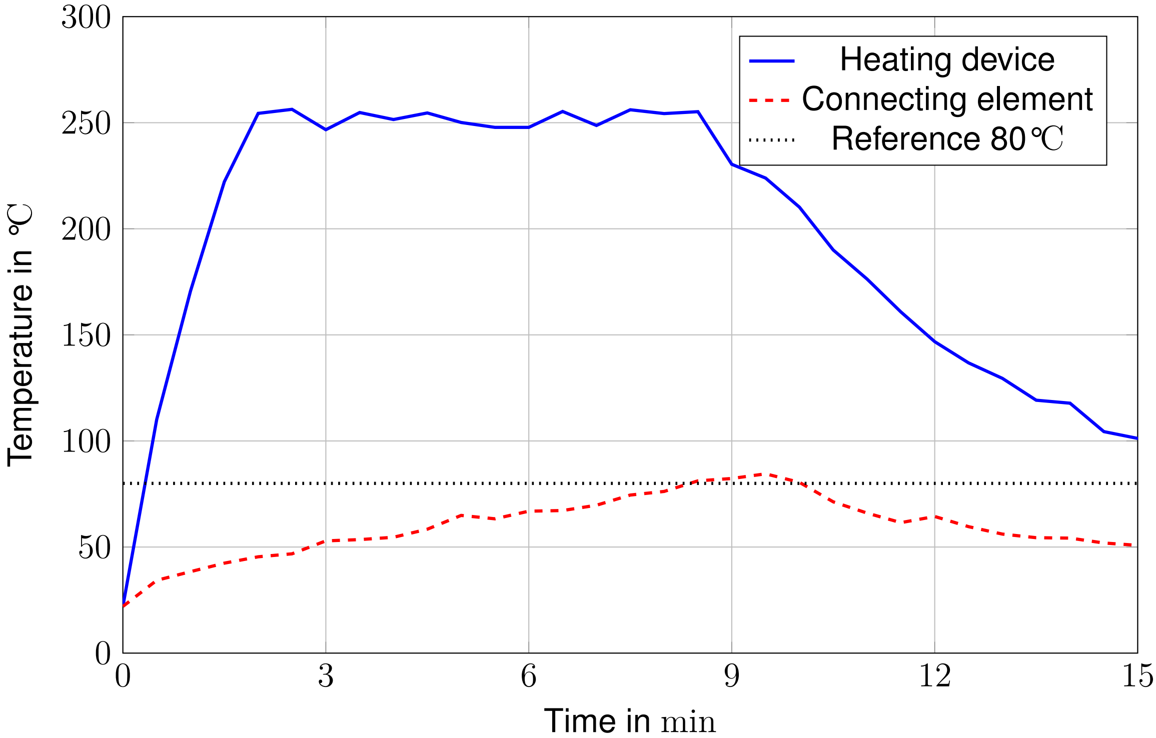


Figure 5.7: Temperature curve during heating cycle

the construction during heating cycles. Therefore a temperature analysis has been carried out as part of the parameter optimisation. To analyse the temperature progression, the temperature on the surface of the connecting element is measured. As a reference value, the temperature of the heating device is recorded. The target temperature of the heating element is set to 250 ℃. This temperature is kept until the connecting element reaches a temperature above 80 ℃. This limit is chosen because it is the motor's maximum operating temperature. After that temperature is reached, the heating element is switched off. Figure 5.7 shows the temperature curve. The heating device reaches its target temperature after 2 minutes. It then fluctuates around 250 ℃ due to the two-point controller. The connecting element reaches the temperature of 80 ℃ after 9 minutes. The temperature then continues to rise but starts to decline after 10 minutes. After 6 minutes of cool-down, the connecting element reaches 50 degrees, and the heating device cools down to a temperature below 100 ℃.

5.6 Communication between PLC and Robot

Three different types of control logic control the 4K-FFF unit. The robot is controlled by the robot controller, which is programmed using Kuka's in-house language, Kuka Robot Language

(KRL). The PLC is managed using its own programming language. All machine instructions for the print path and installation of the inserts are to be specified in the NC code by the user. NC code is generated from the G-code, which defines the pathing of the printer, and the M and G commands required for the installation of inserts. NC code is therefore the interface that the user has to deal with. The other languages only have to be used during setup. Predefined commands manage the communication between PLC and NC code. M and G commands required for the integration process are explained in chapter 5.3.

The communication between the robot and PLC works via a 32-bit connection. The 32 bits are equivalent to the robot inputs 10 to 41. Coordinates, insert data and management commands must be transmitted via this connection. The first 17 bits, which reference inputs 10 to 26 on the robot, transmit the coordinate data in binary code. After the data is transferred, it is deleted in the PLC to avoid faulty multi-transmission of the same values. The values are multiplied by 100 before they are transmitted to make it possible to transmit fractional values. The binary representation is converted back to decimal on the robot by a suitable program and divided by 100 to account for the fractional values. The requested insert number is transmitted to the robot via these bits and converted between binary and decimal in the same way as the coordinate data.

Table 5.2 shows the other input and output values used for communication between PLC and robot. Input 30 is set to true by the command M111, which starts the installation process and gives permission to enter the printing chamber. The command then waits for the robot output 20 to be set true. Input 31 is set to true by command M112, which signals the robot that the installation process of the insert is completed. M112 then waits, until the robot signals, that it left the printing chamber by setting output 21 true. Input 32 is set to true when the installation cycle is completed, and the robot must return its tool to the storage shelf. This command is planned and not implemented during the writing of this thesis. Input 35 is a safety feature that must be set true at all times to allow the robot to move. Output 36 to 39 are used to request data, and input 36 to 39 signal that new data is stored in the PLC. Output 41 is a planned safety feature and is not implemented during the writing of this thesis. The robot's code is written in a manner that detects invalid values and then reports an error by setting output 41, which causes the process to abort, requiring manual intervention.

It has to be mentioned that during the writing of this thesis, it is not possible to detach the end-effector from the robot, as this results in an error that leads to a stop of the 4K-FFF unit and the NC code. This is because the linear motor of the end-effector is implemented as a CNC axis, which is monitored by the PLC as a safety feature. Due to this, the end-effector

Table 5.2: Input and output values of robot

Robot input	Meaning	Explanation
30	all clear	Permits robot to enter printing chamber
31	InsertDone	Reports to the robot, that insert is installed
32	ProgramEnd	Reports that no further inserts are installed in this cycle
35	driveClear	Safety feature, gives permission to robot to move
36	insertReady	Reports, that data for a new insert is ready to transmit
37	xValueReady	Reports, that data for a new X-Value is ready to transmit
38	yValueReady	Reports, that data for a new Y-Value is ready to transmit
39	zValueReady	Reports, that data for a new Z-Value is ready to transmit
Robot output	**Meaning**	**Explanation**
11	vacuum	Activates vacuum gripper
20	startInsert	Requests the PLC to start installation process
21	robotclear	Reports to PLC, that robot left the printing chamber
36	insertRequest	Requests new insert Data
37	xRequest	Requests new X-Value
38	yRequest	Requests new Y-Value
39	zRequest	Requests new Z-Value
41	errorFlag	Reports Error in installation process

needs to be attached during the printing process. Other inserts than threaded inserts can only be installed after the printing process is finished and the printer is moved to a safe location. Furthermore, only one component can be installed after the end-effector is removed, as the removal of the effector stops the NC code. This issue will be addressed in further development by implementing the motor as an NC axis. These can be attached and removed without issues. Implementing the motor as an NC axis will cause changes in the NC code. The G1 and G74 commands will be replaced with M commands that will control the movement of the linear motor. Once the linear motor is implemented correctly, an additional M command will be implemented. This will be the command M113. It will indicate that the installation process for an entire layer is completed and that the robot can return the equipped effector to the quick change storage shelf by switching input 32 of the robot to true. At the time of the writing of this thesis, this would not make sense since the thread effector has to be attached for the 4K-FFF unit to work.

5.6.1 NC Code

Listing 5.3 gives an exemplary NC code for an integration process. The commands are explained in chapter 5.3, and the overall process is explained in chapter 5.4. This example shows the NC code for two inserts of types 3 and 8 that are to be installed. The insert numbers 3 to 6 refer to the threaded inserts of sizes M3 to M6. Insert number 8 is a circuit board, and insert 10 is a washer. Line 1 to 15 are needed for the installation process of the threaded insert of size M3. Line 16 to 21 start an installation process of a circuit board. The insert M3 gets installed at location (100/150/10) with a temperature of 250 ℃. The preheating location is at 3.6 mm, which is travelled to with a movement speed of 90 mm/min. The motor's final location is at 7 mm, which is reached with a movement speed of 30 mm/min. The circuit board is installed at the location (80/100/10).

The process starts with the transfer of the insert data. Command M111 waits until the robot is in position. The heating device is activated, and the motor is referenced. Preheating is started by moving the heating tip to its preheating location. A waiting period elapses until the target temperature is reached. Then the insert is melted into the component. Another waiting period elapses to make sure the insert is fully installed. After the process is finished, the motor is referenced again to move the heating tip to its default position, and the heating device is turned off. M112 waits until the robot is in a safe location outside the printing chamber. The second installation process starts with the transfer of the new insert data. M111 and M112 are waiting for the installation process to be finished.

5.6.2 Robot Code

The code of the robot can be found in listing C.2 in the appendix. It will be explained in detail in this section. First, all variables required for the process are declared and initialised in lines 2 to 22. The "Count" variables register how many threaded inserts of each type have already been used. This causes the robot to move further on the storage module for the pick-up of threaded inserts, depending on the variable's value. The variable "Effector" stores which effector is currently attached to the robot. This variable must be set to 0 in the future code because usually, no effector is attached to the robot when it is in an idle position. However, due to the problems mentioned above with the CNC control, the thread effector must always be coupled to the robot. The variable "Insertnumber" stores the transferred value, which insert is to be used. The variable "XIntegration" is a coordinate variable that stores the coordinates

Table 5.3: Exemplary NC code for installation process

```
G1 X300 Y300 Z250 F1000
V.E.Insert.xPos = 100
V.E.Insert.yPos = 150
V.E.Insert.zPos = 10
M110 = 3
M111
M108 = 250
G74 QH = 1
G1 QH = 3.6 F90
M107
G1 QH = 7 F30
M107
G74 QH = 1
M108 = 0
M112
V.E.Insert.xPos = 80
V.E.Insert.yPos = 100
V.E.Insert.zPos = 10
M110 = 8
M111
M112
```

of the target of the integration process. "Correction_Z" is needed for the thread effector. Due to the overload sensor, which allows some degree of play, the mounting of the thread effector is slightly tilted, which is compensated for by an offset of 1.5 mm. The commands in lines 25 to 36 reset all output values of the robot to the default values so that the program always launches in the same state. Wait commands between setting outputs true and false are required because if an output is switched on and off without a break, there is not enough time to cause a mechanical reaction. In line 39, a move command ensures that the thread effector assumes a default position at the start of the program. This command must be replaced in future code. A movement command to the home position will be placed here, such as in line 247.

In line 42, a while loop starts without a condition. This loop is run continuously. The loop starts by setting the output "robotclear" false so that together with the M112 command, the printer is prevented from moving while the robot is in the printing chamber. Lines 48 to 60 cause the robot's tool to be transported back to the storage shelf, after the M113 command has been called up in the NC code. For this purpose, the subroutines SWS_Back_ThreadEff()

and SWS_Back_Vacuum() are called, which are explained in chapter 5.1. In lines 63 and 64, the coordinate and insert data are transferred from the PLC to the robot. For this the subroutines getInsertFromPLC() and getPointFromPLC() are called. One of the subroutines will be explained below.

Lines 67 to 94 select the correct effector for the requested insert. This code section must be adapted if the quick change system is extended by another slot. In lines 97 to 168, the position on the passive module and the correct Z-value for the installation are defined depending on the requested size of the threaded insert. In lines 171 to 225, the installation procedure for threaded inserts is processed. First, the coordinates are transferred to the points that are to be approached. Then the robot moves by a PTP movement, identified by "SPTP", to a pre-position near the storage shelf. It moves to a point above the insert and then moves the tool to the insert with a slow linear movement, indicated by "SLIN". The gripper of the thread effector is closed by activating output 3. The robot then moves the effector towards the door, passing through predefined points that prevent a collision. It waits until input 30 is changed to true, which is done by M111. The robot then enters the printing chamber and places the insert in its intended position. The insert is released from the gripper by actuating outputs 3 and 4. With the movement in line 208, the robot's repositioning is performed, compensating for the misalignment of the melting tip and the jaws. Output 20 is set to true, which starts the installation process, as command M111 waits for this output to be set to true. Subsequently, the robot waits for input 31 to be set true, which is done by command M112. After the insert is fully installed, the robot sets output 20 to false and returns from the printing chamber by the same route it took to get there. When the robot is at its initial position, it sets output 21 to true to indicate that it is outside the printing chamber.

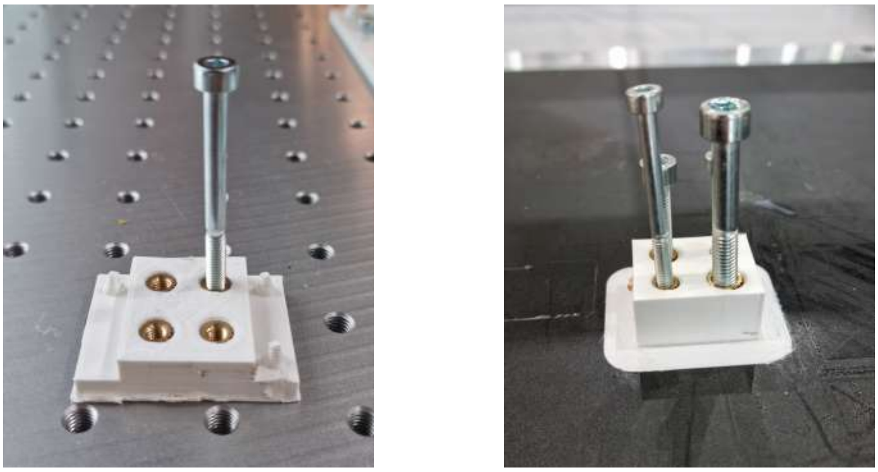
Lines 228 to 268 show the installation procedure using the vacuum gripper, and lines 272 to 316 show the procedure for the jaw gripper. In principle, the sequence is the same as the process of the thread effector, except that the effectors must be controlled differently. It is not necessary to wait for the completion of an installation process initialised by the PLC, so that a block that sets both output 20 and output 21 to true at the end of the process is sufficient. For the vacuum gripper, output 11 is used, which activates the vacuum generator. For the jaw gripper, the same outputs 3 and 4 are used as for the thread effector, but in reverse order, since the jaw gripper is used as an internal gripper. Therefore, the gripper is closed at the beginning of the program in line 281 to ensure that the jaws are in the correct starting position.

The subroutine getInsertFromPLC() is shown in listing C.3 in the appendix. It is defined as a function, that returns an integer value. The variables "Error" and "Insertnumber" are defined and initialised at the start. By setting the output 36 to true, the robot controller requests transmission of an insert number. It then waits until the PLC transmits, that new data is available by setting input 36 to true. Another subroutine commValue() is called, which converts the number, that is transferred as a binary number back to a decimal value. The value is stored in the variable "Insertnumber" and is divided by 100. It is then validated by checking if the value is in the range of one to sixteen. If the value is out of this range, the "Error" variable is set to one, resulting in the output 41 being set to true. This will lead to the stop of the process, but the command is not implemented in PLC during the writing of this thesis. At the end of the program, the value of "Insertnumber" is returned. The PLC erases the stored data after transferring it. Therefore no outdated data can be transferred mistakenly. When no new data is available, the robot program waits in line 10 for input 36 to be true, until new data is transmitted to the PLC by the NC code. The program stays in this state while other commands, such as a regular printing process, are executed in the NC code.

5.7 Automated Installation of Inserts

After the parameters for the melting process are optimised and the robot's programming is completed, the compatibility of the thread effector with components printed on the 4K-FFF unit must be validated. During the manufacturing process, the robot is operated in the automatic mode, with the program "Master" as the selected routine, which is explained in the previous chapter. For the validation, two demonstrator components with four cavities each are printed. At the end of the printing process, threaded inserts are installed into the component. The robot and print bed coordinate systems were already aligned by A_Schadt (2022). This measurement is adopted without changes. The components are shown in figure 5.8. Component (a) contains 4 inserts of size M4, component (b) contains one insert each of type M3, M4, M5 and M6. The bolts in the parts are used to demonstrate the correct installation angle. It has to be mentioned, that the cooling of the 4K-FFF unit cannot be used while the thread effector is mounted on the robot, as the cooling is not regulated by a valve. This leads to continuous leakage of air. Although this leakage is intended, as the air is used as a coolant in the printing process, this leads to a problem. The maintenance unit detects the leakage and therefore reduces the pressure in the system. This leads to insufficient pressure in the overload sensor, which triggers an error.

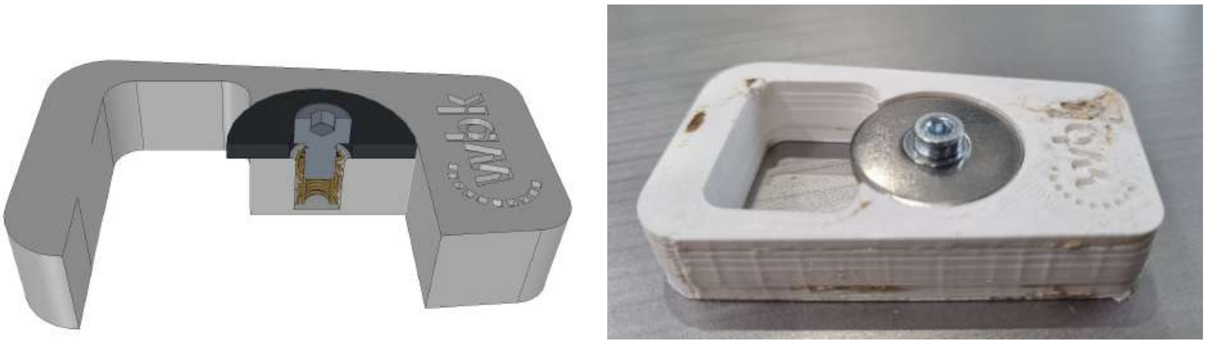
Two further demonstrator parts are printed, to validate the compatibility of the newly installed



(a) (b)

Figure 5.8: Demonstrator parts for 4K-FFF unit

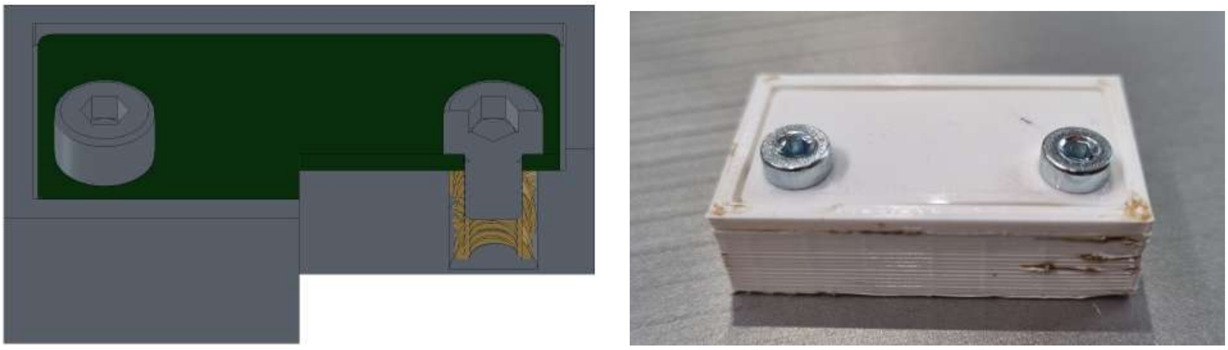
quick change system with the thread effector, the vacuum gripper, the jaw gripper and the 4K-FFF unit. Since only two effectors can be stored in the quick change system, the two demonstrator parts can only include two different kinds of inserts each. Figure 5.9 (a) shows the CAD model of the demonstrator part for the combination of the jaw gripper and thread effector. The part is a bottle opener equipped with a washer that offers metal as a contact surface with the bottle cap. Underneath the washer sits a threaded insert. This is used to hold the washer in place by fixating it with a bolt. Figure 5.9 (b) shows the finished part.



(a) (b)

Figure 5.9: Bottle opener as a demonstrator for the functionality of the jaw gripper

Figure 5.10 (a) shows a circuit board holder, which illustrates the capability of using a vacuum gripper and thread effector on the same part. Two threads of type M4 are installed mid-process, and then a dummy part, of the same size as a circuit board is installed at the end of the printing process. The print result can be seen in figure 5.10 (b). The results of the printed parts will be discussed and evaluated in the following chapter.



(a) (b)

Figure 5.10: Circuit board holder as a demonstrator for the functionality of the vacuum gripper

6 Evaluation

This chapter discusses the results of the development and integration of the end-effector and quick change system. Furthermore, the print results of the demonstrator components are evaluated, and the added value of the newly installed components is analysed.

6.1 Assurance of the Fulfilment of the Requirements for End-Effector

The requirements for the development of the end effector are listed in table 4.1. The newly developed effector is designed to be attached to the industrial robot. The compatibility is shown in the previous chapter in the parameter optimisation and manufacturing of the demonstrator components. It is shown that inserts can be installed perpendicular to the print bed. No definitive statement can be made on the ability to install inserts with a tilted angle, as the software and control system are currently not designed for installing inserts in tilted angles. However, the effector's hardware allows insert transport at any orientation. If the software enables the effector's correct positioning, installing threaded inserts with a tilted angle is technically possible. The requirement to be able to install several threaded inserts in one component is fulfilled, which is shown with the second demonstrator component. One type each of threaded insert of sizes M3 to M6 was successfully installed. The heat source is controlled with a two-point controller and is therefore adjustable in temperature. To ensure reliable operation, calculations were carried out during the design phase, so that no jamming of the jaws or jamming of melting tip and insert could occur. During the experimental phase, no jamming of any kind occurred. This confirms the correctness of the calculations. Repeatability is further demonstrated in the course of the parameter optimisation. Eight inserts of each type were installed in one part, resulting in a total of 34 installed inserts in a row. All inserts were successfully installed. In none of the installation processes, an insert was installed incorrectly if all input parameters were implemented correctly. The correct depth of the installation process is ensured by parameter optimisation. Correct positioning of inserts is achieved by the correction explained in 5.5.2. This correction is needed due to the misalignment of the heating tip and gripper jaws. In a new iteration of the design process, the connecting element and the aluminium block, which contains the heat source, should not be connected by a conventional heat break. Instead, a custom-made heat break should be manufactured. This way, the connection can be made with a fitting instead of a thread, which improves the accuracy of the connection. Likewise, the connection of the melting tip should be changed to a fitting for the same reason. Several factors are significant for the accuracy of positioning. The positioning accuracy of the robot, the general accuracy of the FFF process, the misalignment of the melting tip and the gripper jaws, and the overload sensor introduce an unquantifiable inaccuracy into the process. Despite these inaccuracies, it has been repeatedly demonstrated that threaded inserts can be successfully installed. However, the tolerances can lead to slight tilting of the installed threaded inserts.

The requirement to store the inserts in a magazine is not fulfilled. Instead, a storage shelf is set up, that can hold ten pieces per insert type, which is sufficient for conventional components. If more than ten inserts of one type need to be used in a part, the shelf can be adapted to hold more inserts of a particular type. The heat resistance is demonstrated in chapter 5.5.2. It was found that after 9 minutes, the connecting element reaches a critical temperature of the electric motor. An installation process from an initial cold state takes 3 minutes, with a preheated melting tip it takes 1.5 minutes. In 9 minutes, five threaded inserts can be installed. After the connecting element reaches the critical temperature, it takes time for the motor to reach this temperature because the motor shaft, which is the link between the connecting element and the motor, is made of steel, which conducts heat poorly compared to aluminium. Therefore, at least 5 melting processes can be performed without an interruption, which is sufficient for standard components. In the choice requirement between electric and pneumatic actuators, a combination of both has been chosen to take advantage of the respective actuators' strengths. The requirement for a lightweight and compact design that is also robust was taken into account in the design process. The most compact actuators that are available have been chosen. The design is light and can therefore be transported with the robot. It also fits the selected quick-change system. Robustness is ensured by using 8 mm thick aluminium plates as the housing. Sensitive components such as the reference switch and melting tip are safely stored inside the effector during critical transport operations. The requirement for preferential use of purchased parts can only be met to a limited extent. Several components have to be manufactured in-house for the assembly of the thread effector. In order to minimise the workshop effort, the raw material was provided by a supplier in the correct outer shape dimensions.

The mandatory requirement for control by the HybridPlaner can only be met to a limited extent. The HybridPlaner in the version available at the time of writing this thesis (August 2022) is not capable of successfully creating the NC code for the thread effector. In addition, some bugs in the program make data import difficult and require manual post-processing. The HybridPlaner, in its current form, only serves to transform the G-code from the slicer into NC code that the 4K-FFF unit can interpret. The installation processes must then be implemented with manual post-processing. This allows a functioning NC code to be created. It is worth mentioning that a new version of the HybridPlaner is being programmed in parallel with this thesis, which will enable the planning of installation processes with the thread effector. The requirement for simple control can be met to a certain extent. The implementation of the effector is complex, since several effectors are connected to the PLC and have to be controlled separately. However, this is not a problem for the end user. The user only has to specify the required parameters installation depth, pre-position for preheating, melt-in temperature and additional waiting time according to the selected insert type. These values should be adopted from the parameter optimisation and are listed in table 5.1. In the choice requirement for a permanently active or temporarily activated heat source, the decision was made in favour of a temporarily activated heat source to prevent overheating.

6.2 Assurance of the Fulfilment of the Requirements for Quick Change System

The quick-change system is established together with an energy chain as proposed by A_Schadt (2022), to improve the overall system. The requirement for compatibility with existing tools is achieved through adapter plates. The compatibility was shown by assembling and using all the effectors in combination with the quick change system. Compatibility with the 4K-FFF system was ensured by mounting the storage shelf on the passive module. By integrating the quick change head into the air pressure system and controlling it via the robot, the quick-change system is fully compatible with the machine and can be operated. The requirement for a low price was considered by selecting the most cost-effective model compatible with the robot. The quick-change system is expandable, with space for at least one additional storage module on the storage shelf.

6.3 Evaluation of the Demonstrator Components

The components from chapter 5.7 uniformly show poor printing results, even though the printing parameters optimised by A_Schadt (2022) are used. It can be seen that the layers adhere badly to each other, and details are poorly resolved. Furthermore, brown impurities can be seen in the material. This is due to problems in feeding the filament, which leads to too long contact of the filament with the hotend. In general, problems have occurred with feeding the filament, leading to clogging of the nozzle and insufficient material being fed, so printing processes have to be restarted repeatedly. A_Schadt (2022) introduces a newly designed cooling system for the filament in his thesis and concludes that the cooling system contributes significantly to the improvement of part quality. Due to the above-mentioned problems with the overload sensor, this cooling can currently not be used with the thread effector. When interrupting the printing process to place inserts, it was found that too little material was initially extruded in the subsequent layer. This is due to the distance between the outlet from the nozzle and the feeding motor. To correct this, material should be extruded into a corner of the print bed after each installation process before the printing process is continued, so that any impurities that occur during waiting are removed, and the new layer is printed straight away with the correct amount of extruded material.

Regarding the handling process, only two of the three effectors can be used in an automated process. This can be resolved by adding additional space to the quick-change system. The vacuum gripper still has the problems already described by A_Schadt (2022), although the air supply has been optimised by using a larger hose diameter. The suction force of the vacuum gripper is barely sufficient to transport very light components. In addition, the components can tilt because the contact surface of the gripper is very small. In general, components that are not rotationally symmetrical currently have to be aligned by correct positioning on the passive module, which makes the supply process inflexible. In the future, an additional parameter should be introduced to allow rotational alignment of the components by the robot.

Apart from the above-mentioned problems, the demonstrators show that the printing process, the interruption of the process, and the installation of inserts are functional both mid-process and at the end. In addition, it is demonstrated that the quick-change system and thus the use of several tools in one process is possible without any problems. Finally, the components show that integrating any size of threaded insert inside the printing chamber is possible with the newly developed thread effector.

6.4 Additional Value of the newly added Components

The quick-change system allows tools to be changed automatically. This enables several insert types to be installed into a component without requiring manual interaction. The newly developed effector can grip, heat, and install threaded inserts. As a result, threaded inserts can be melted into components automatically. The demonstrator components presented in chapter 5.7 were manufactured while the robot was in automatic operation. This means no operator interaction is required once the printing process starts. With the help of these components, the newly created robot code is therefore evaluated and suitable for the automated integration of different insert types. All in all, the newly introduced elements increase the level of automation of the 4K-FFF unit.

7 Conclusion and Outlook

7.1 Conclusion

Currently, no process is described in the literature that is capable of automated production of function-integrated components by combining the FFF process with subtractive manufacturing and usage of conductive filament. A process like this is relevant to enable the production of custom design components with included sensor components which can be used for process monitoring in new propulsion concepts for electromobility. A suitable solution is the 4K-FFF unit at WBK, which is this thesis's subject. It is equipped with four extruders, a milling head and a handling module with an industrial robot, enabling it to produce function-integrated components. Threaded inserts are used for contacting and joining of function-integrated components. Currently, no tools or machines can automatically install threaded inserts into custom plastic components, as they are produced in the FFF process. A high degree of automation of the 4K-FFF unit is desired, and therefore threaded inserts need to be installed automatically. This thesis investigates techniques to overcome the lack of options to automate this process. For this purpose, a solution to automatically include threaded inserts into parts produced with the 4K-FFF unit is developed based on the VDI2221. The result is a newly developed effector for an industrial robot capable of automatically installing threaded inserts into components manufactured with FFF.

The newly developed tool is implemented together with a quick change system, which is introduced to increase the level of automation of the 4K-FFF unit. An energy chain is added to the industrial robot for the hardware implementation. The software of the 4K-FFF unit is adapted to allow for the control of the newly developed effector. The result is a standardised NC code to which the user has to transfer the operating parameters for the specific insert type. Parameter optimisation is carried out to determine the ideal operating parameters for the newly developed effector. Lastly, several demonstrator components are produced to validate the functionality of the new effector as well as the functionality of the quick change system.

The added improvements enable the fully automated production of function-integrated parts by combining standard filament, conductive filament, subtractive manufacturing and implementation of external components. The installation of external components was improved by installing the quick change system, which makes automated tool changes possible. It was furthermore improved by the implementation of the newly developed effector, which extends the system with the capability of automatically installing threaded inserts.

In summary, the level of automation of the 4K-FFF unit was increased by developing and introducing a new effector capable of installing threaded inserts and by implementing a quick change system.

7.2 Outlook

The most urgent adaptation, that must take place before the 4K-FFF unit can be used for the automated production of function-integrated components, is the further improvement of the HybridPlaner, which is the software used for planning all manufacturing processes of the 4K-FFF unit. This process is currently under investigation in a separate project and not part of this thesis. In addition, some adjustments to the PLC are required. Most important is establishing the effector's motor as an NC axis, so that the separation of the effector from the PLC can be executed without problems. Furthermore, the M113 command must be implemented to enable several successive installation processes without interruption by tool changes. As a new safety feature, error detection during the transmission of insert data, which is already included in the robot program, must be established in the PLC. As an additional safety feature, the inductive sensors of the quick-change system may be installed to provide feedback on whether a specific tool is located in its designated storage module. For this, the hardware must be installed on the quick-change system and connected to the PLC. In addition, the communication of the PLC with the robot must be adapted to enable the reporting of the tool status. Moreover, the robot code must be adapted in order to be able to recognise and react to the reported status. The quick change system should be extended by another module so that all the currently available effectors can be used.

Apart from the necessary adaptions in the software, the hardware of the end-effector can be optimised in a future iteration of the design process. As stated before, the alignment of gripping jaws and melting tip was a challenge in the assembling process. To simplify the alignment, the connecting element and the aluminium block, which contains the heat source, should not be connected by a conventional heat break. Instead, a custom-made heat break should be manufactured. This way, the connection can be made with a fitting instead of a thread, which improves the accuracy of the connection. Likewise, the connection of the melting tip should be changed to a fitting for the same reason.

Due to the newly installed energy chain, the housing of the printing chamber had to be opened. If the heating of the printing chamber is to be used in the future, the chamber must be sealed again by modifying the hydraulic door. The vacuum gripper should be replaced by a model with a larger contact area, and the vacuum generator needs to be replaced by a more powerful model to ensure safety, when transporting circuit boards, and to enable the transport of heavy components. The cooling must be controlled with a solenoid valve to enable simultaneous cooling of the extruder and overload sensor operation. This measure should improve printing results. After implementing the listed improvements, the function of the entire process for producing function-integrated components should be demonstrated by using several filaments, milling procedures and all effectors in one part.

List of Figures

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Appendix

Drawings End-Effector

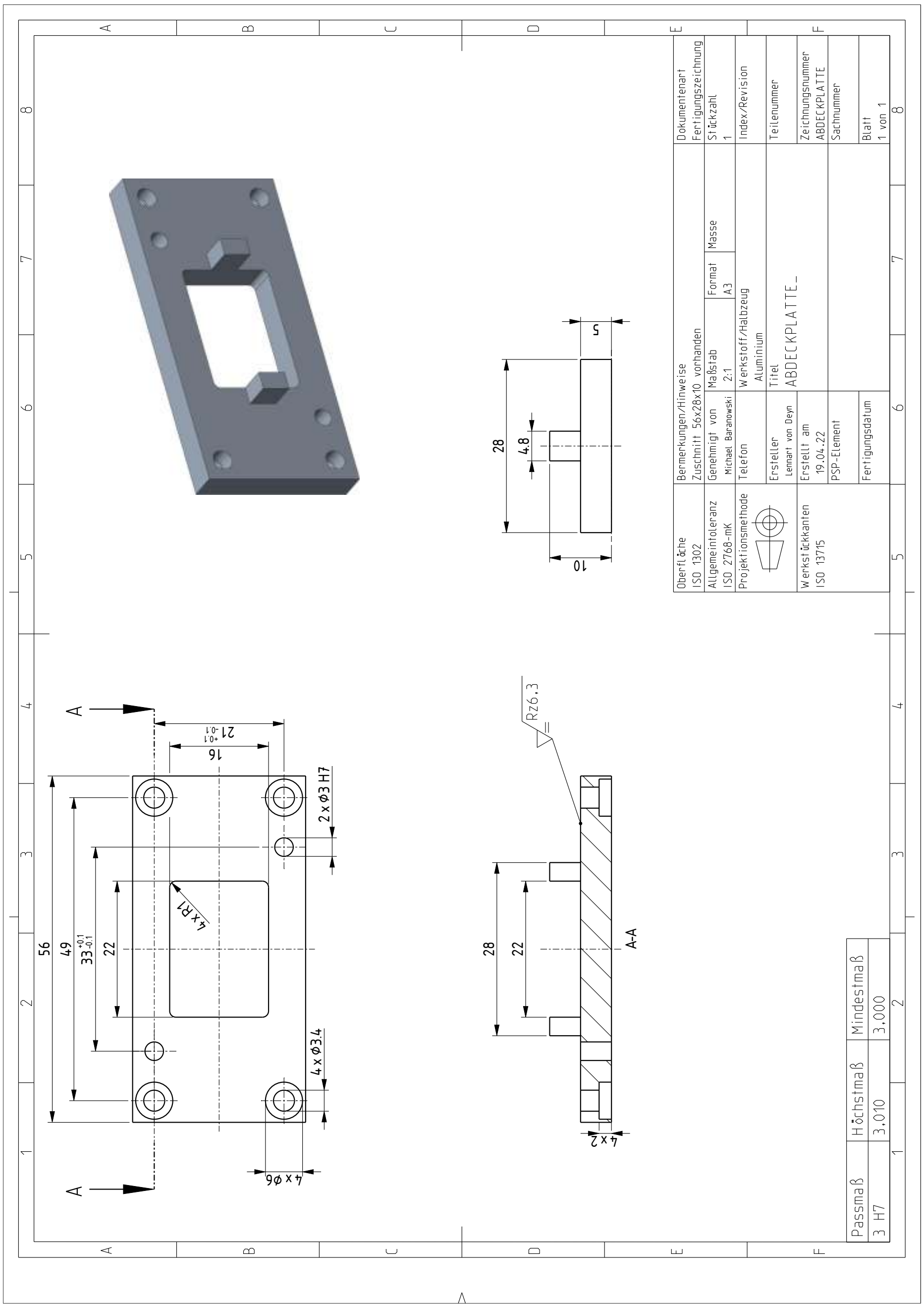


Figure A1: Drawing cover plate

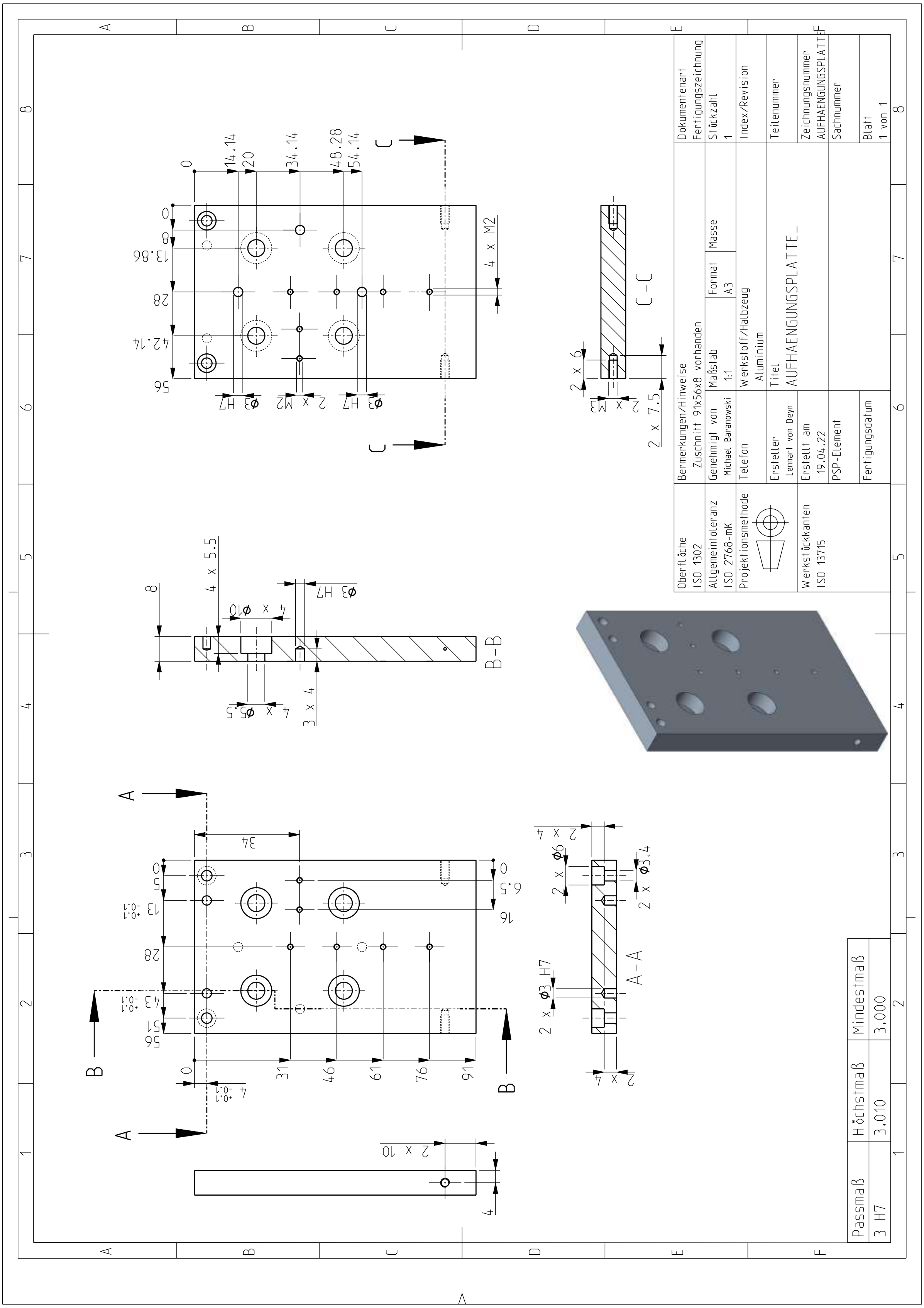


Figure A2: Drawing back plate

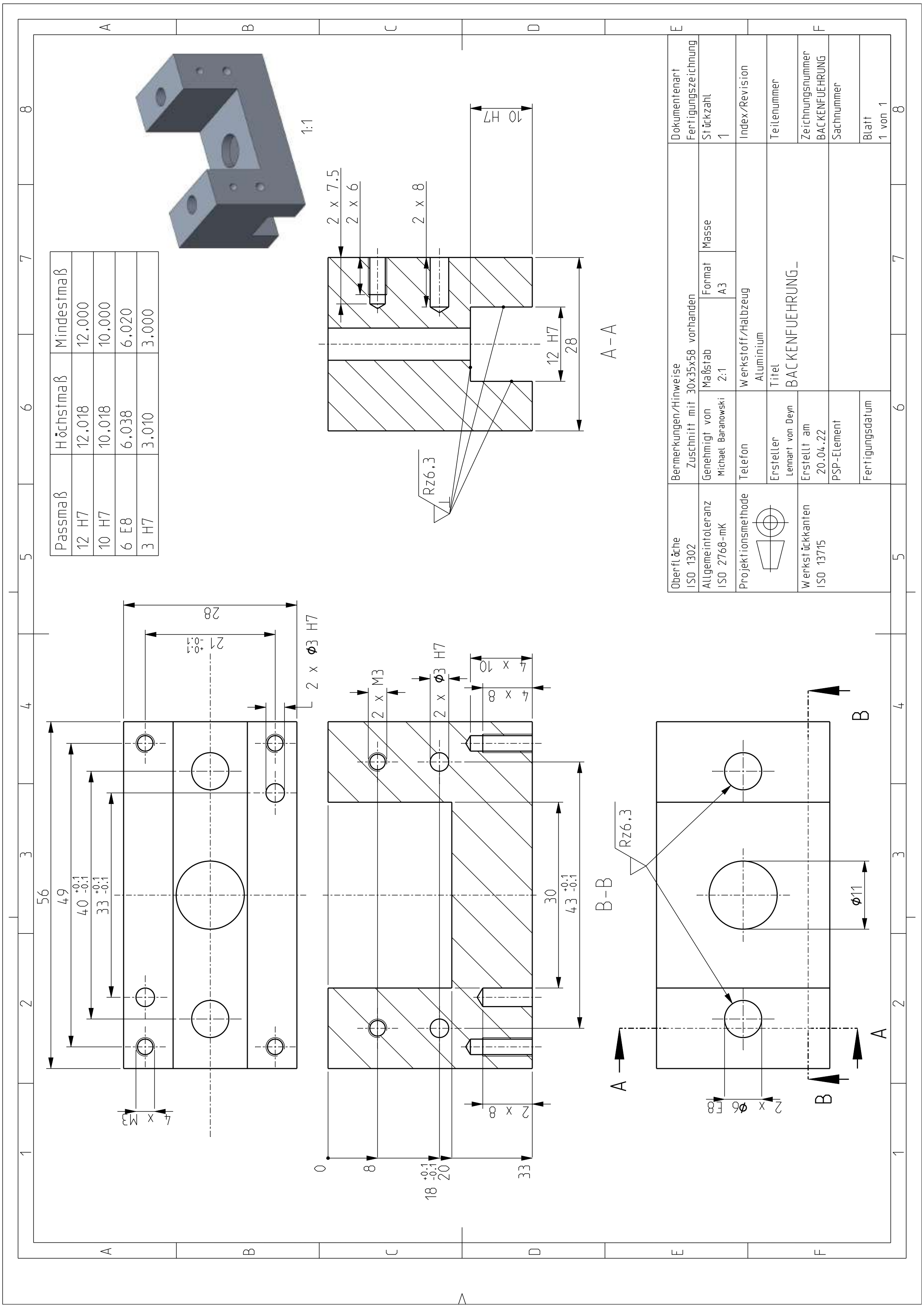


Figure A3: Drawing gripping jaw guide

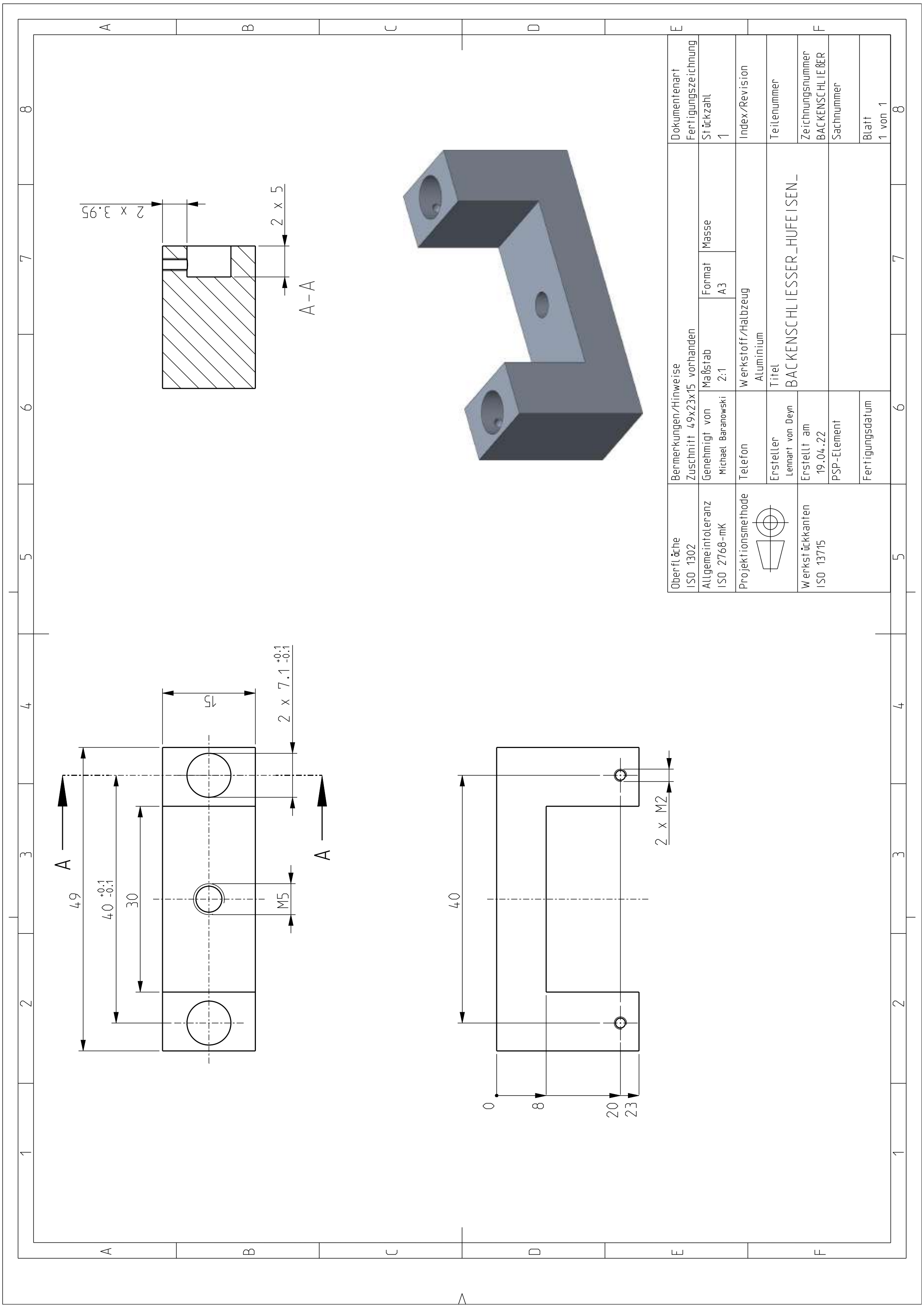


Figure A4: Drawing U-shape part

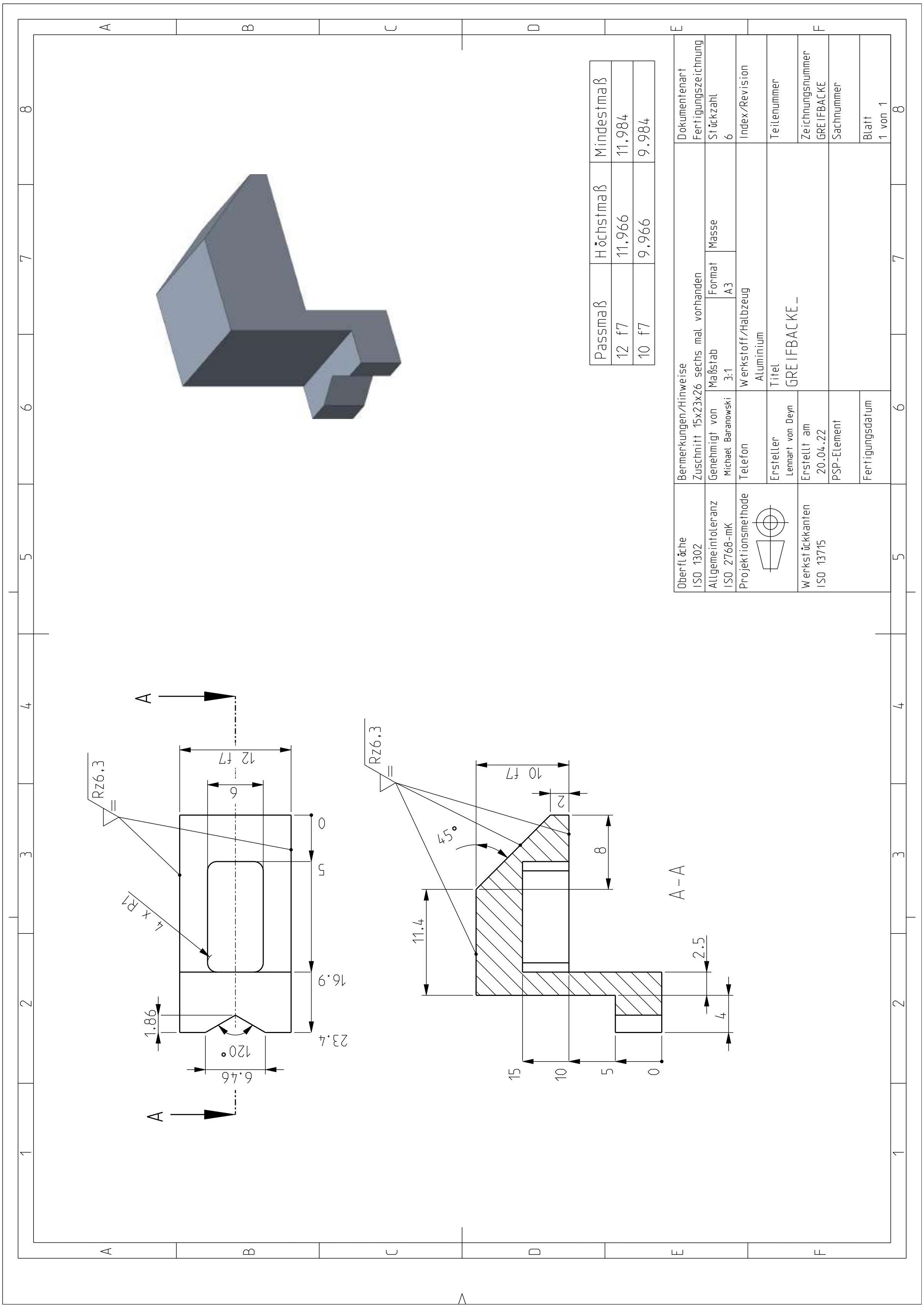


Figure A5: Drawing gripping jaw

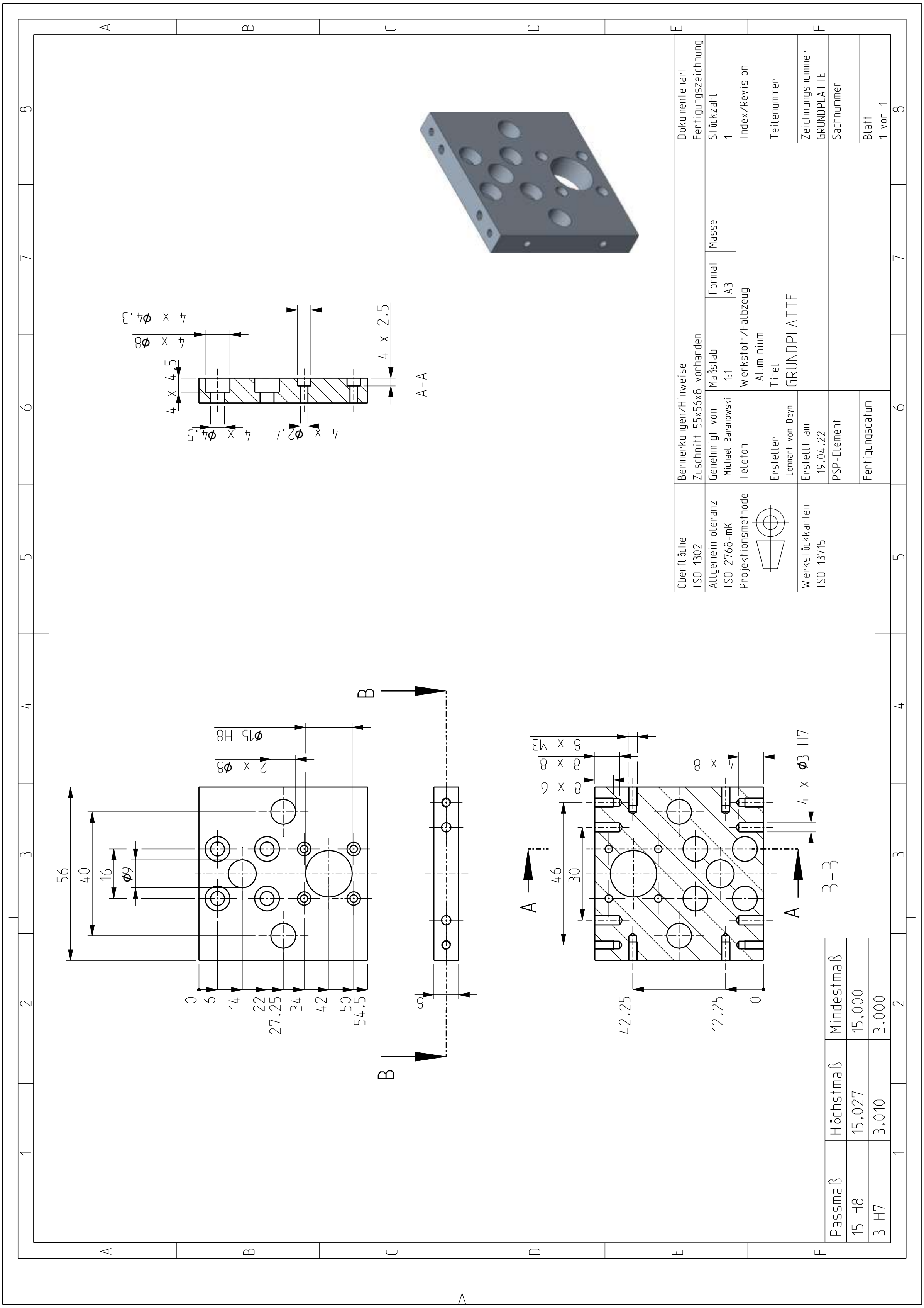


Figure A6: Drawing ground plate

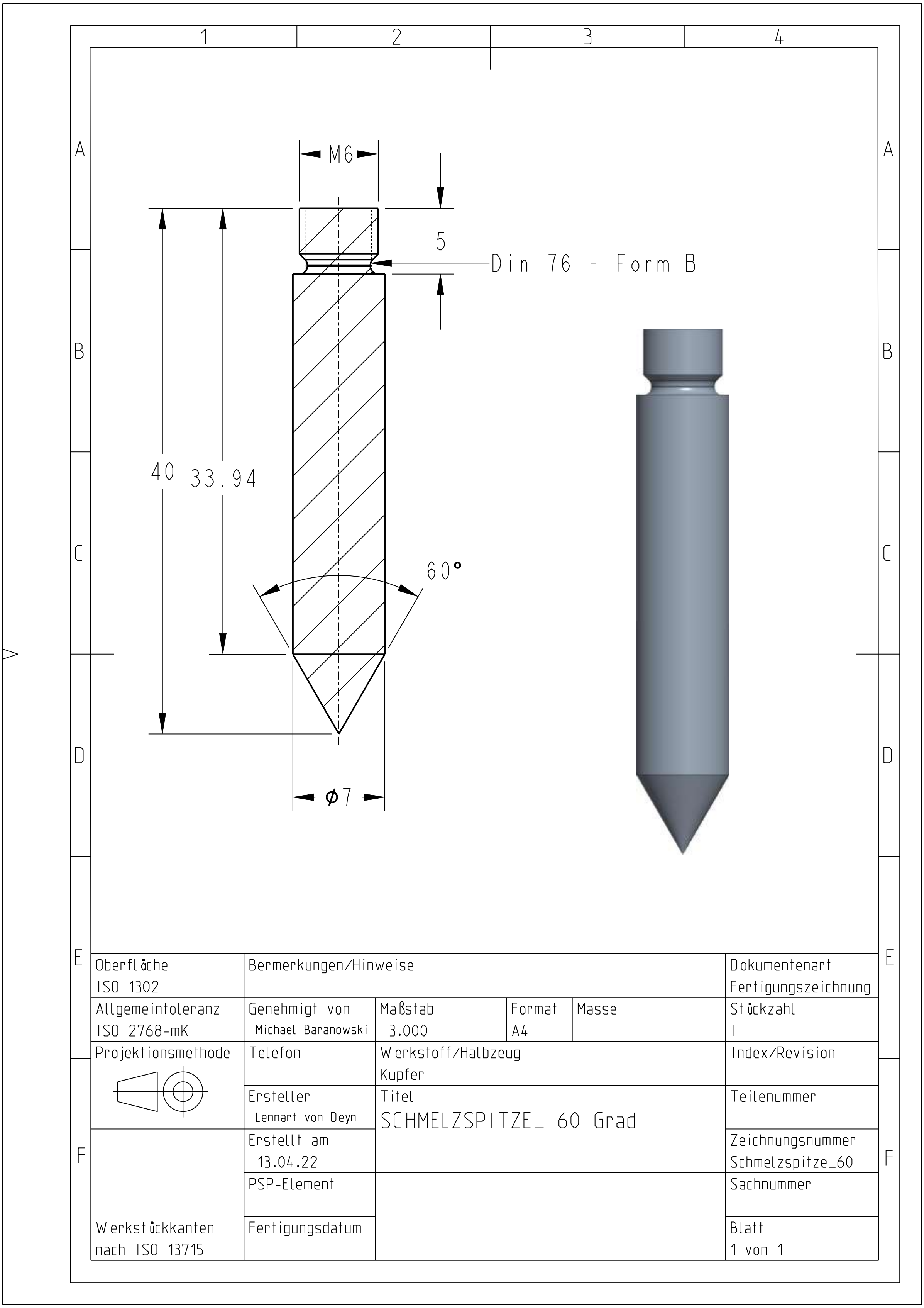


Figure A7: Drawing melting tip 60 degree

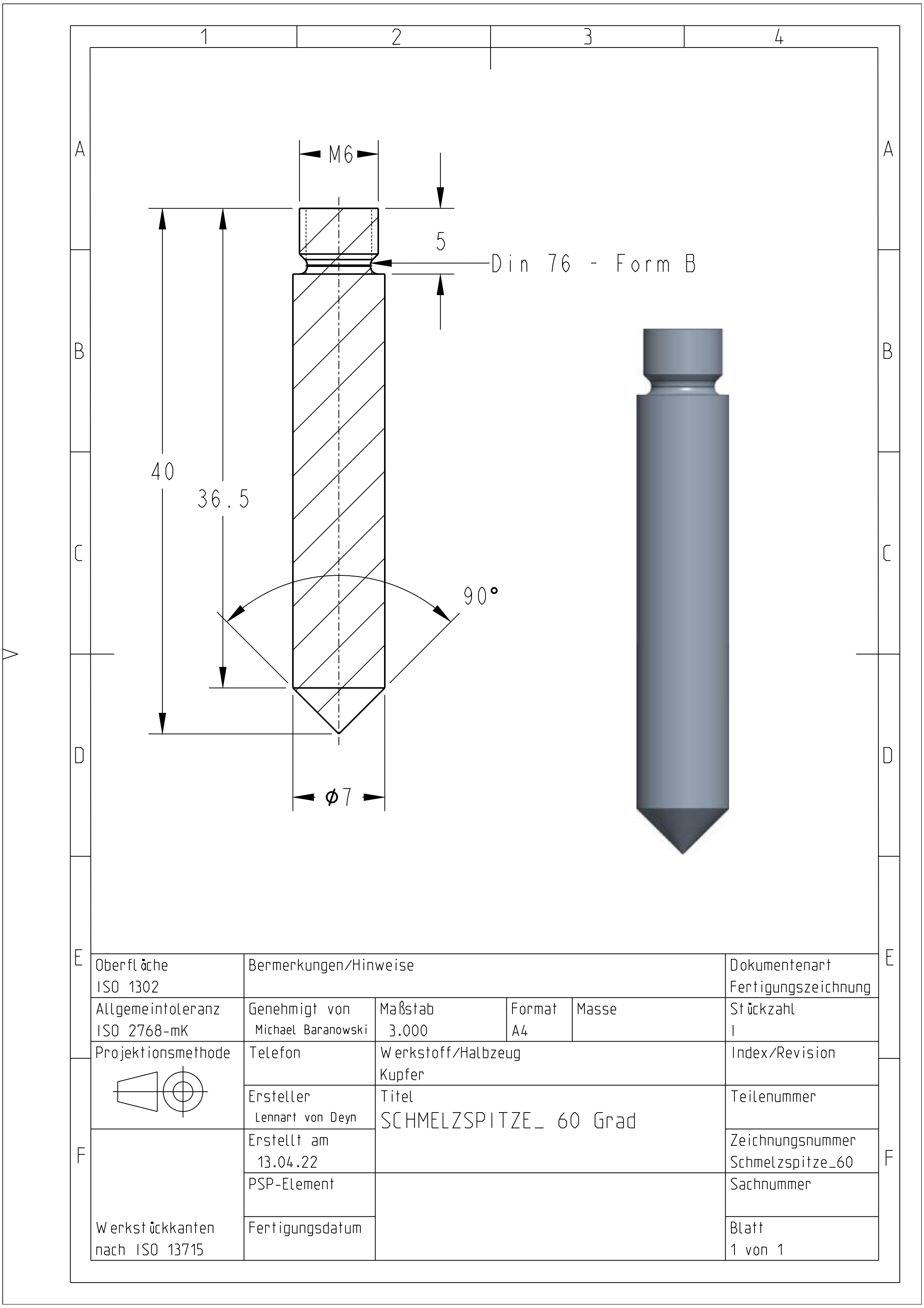


Figure A8: Drawing melting tip 90 degree

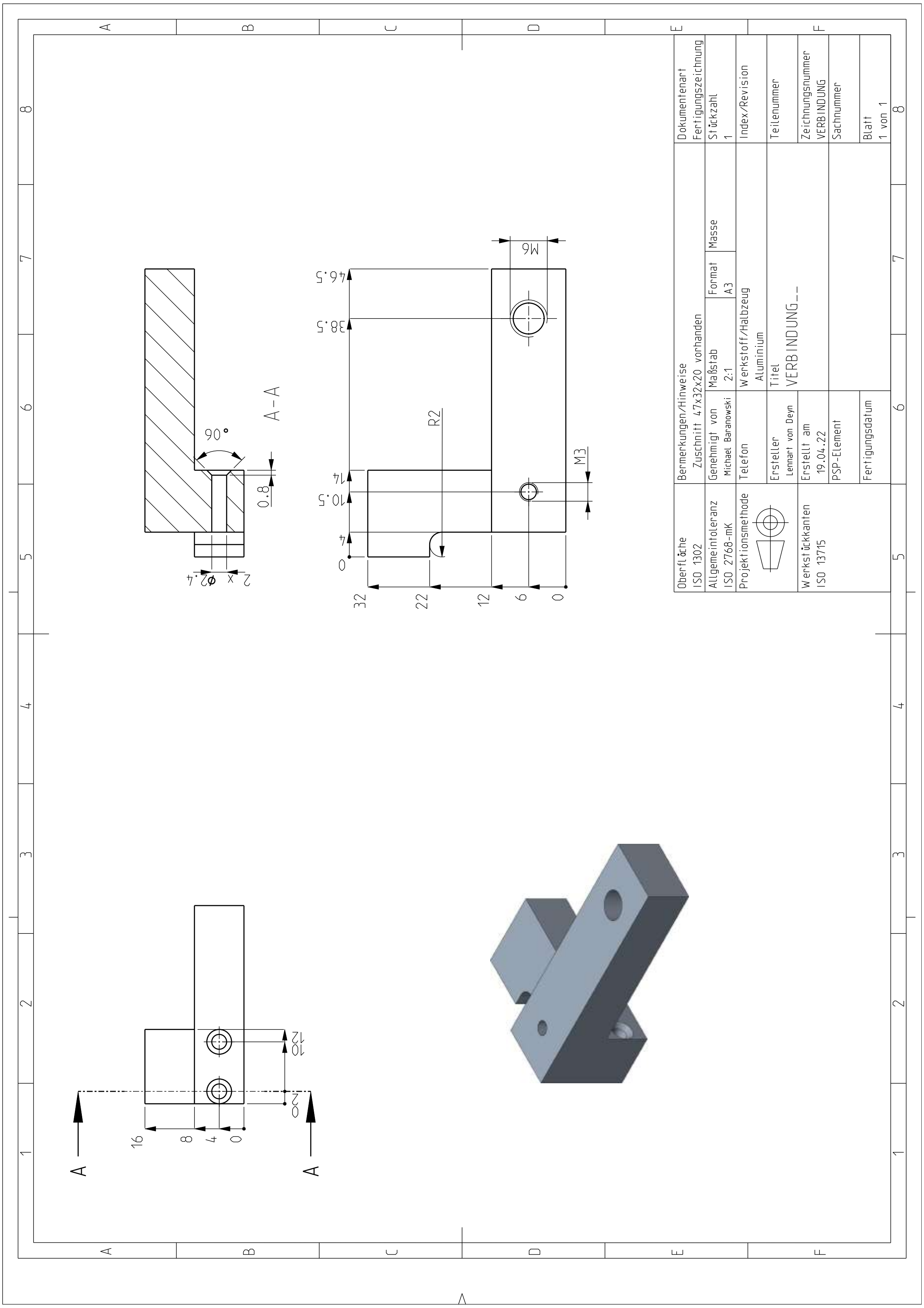


Figure A9: Drawing connecting element

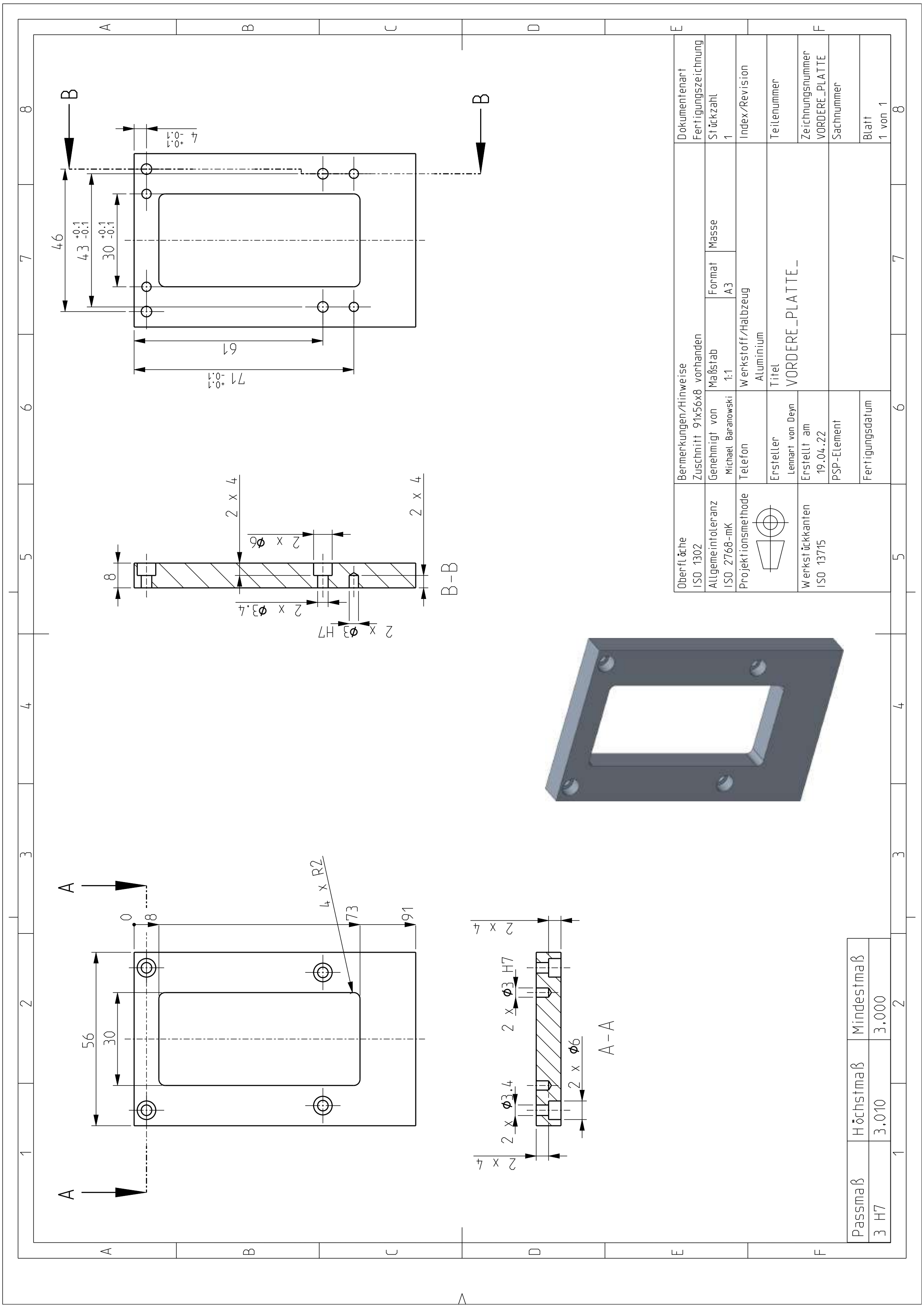


Figure A10: Drawing front plate

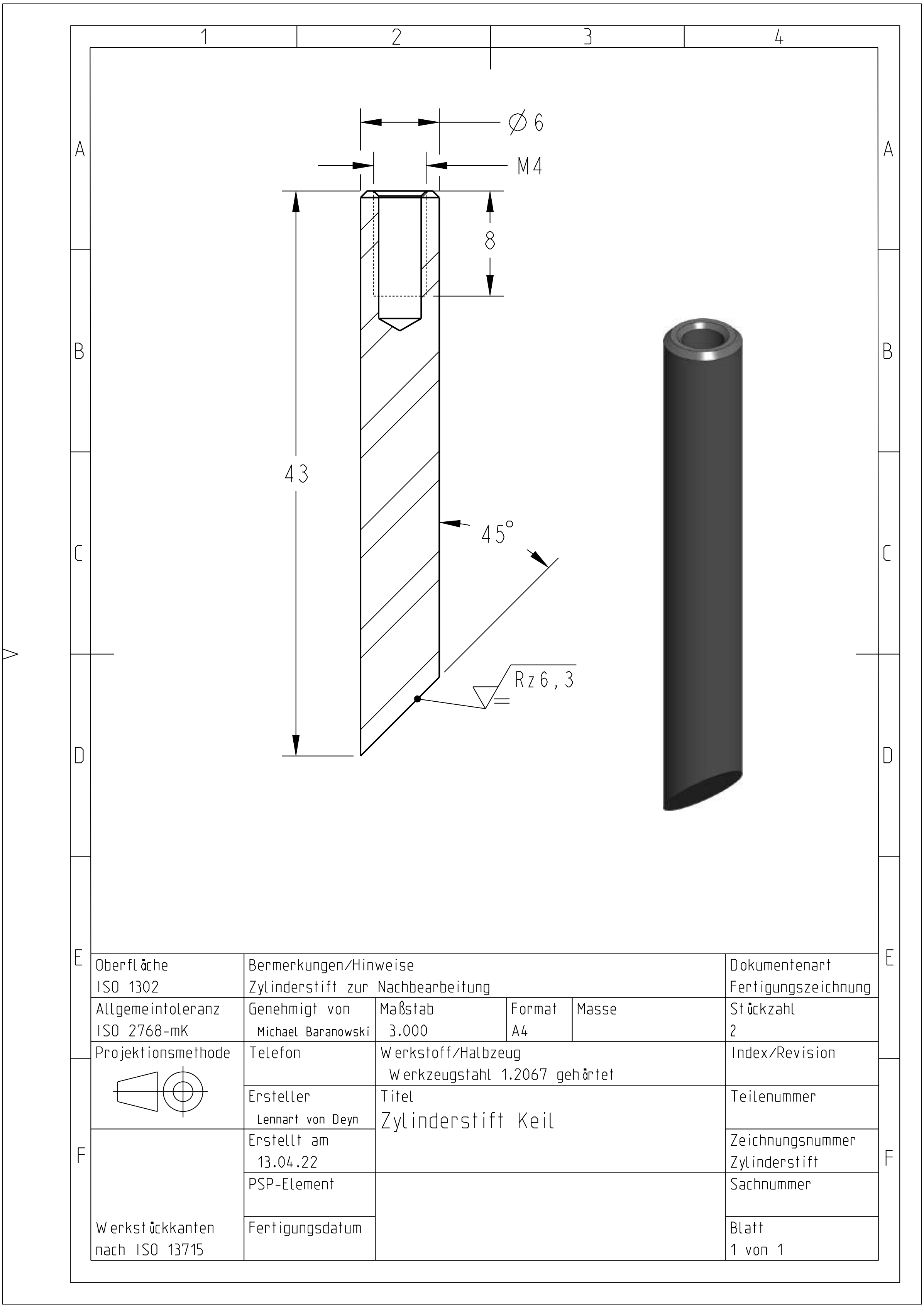


Figure A11: Drawing wedge

Drawings adapter plates

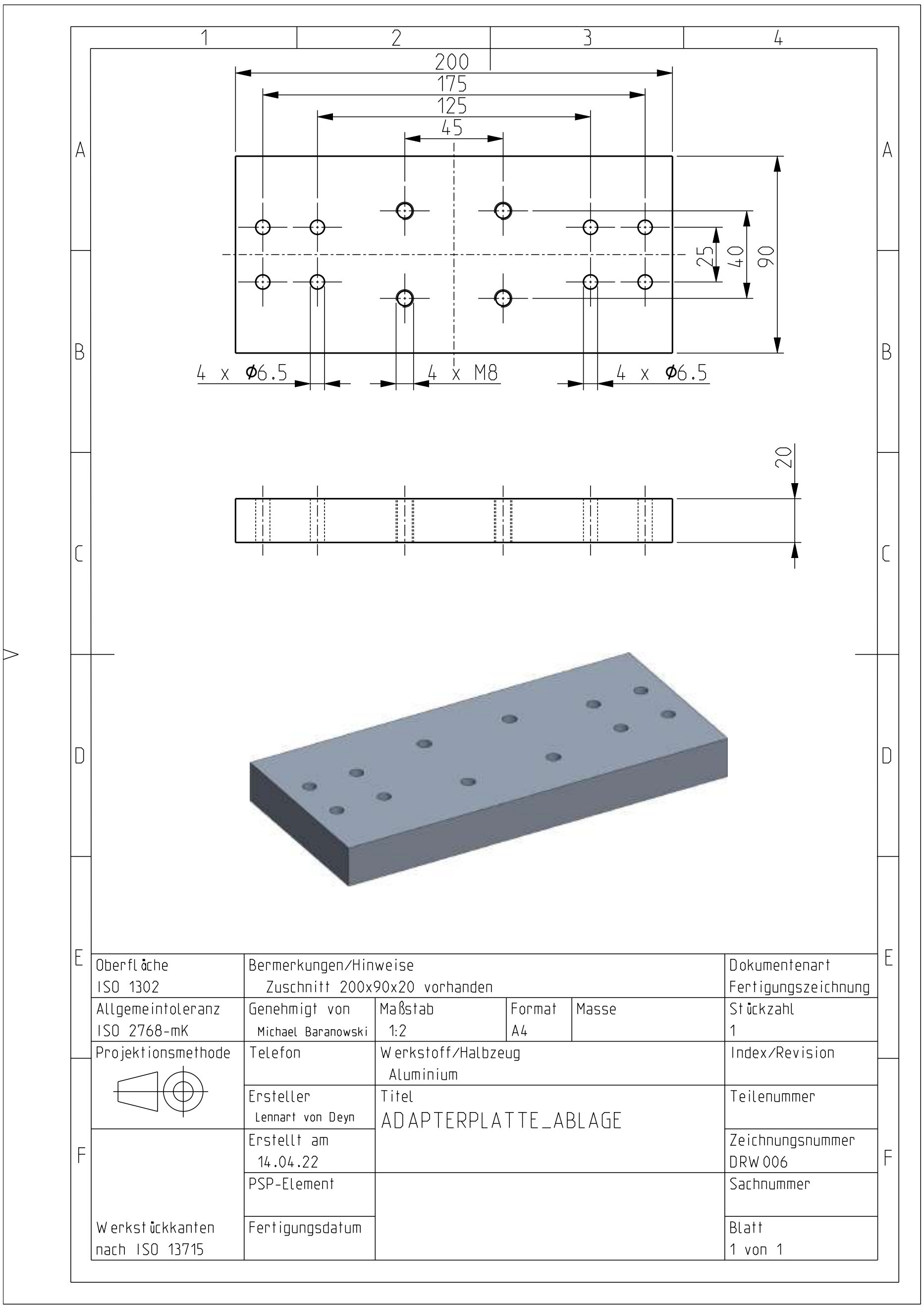
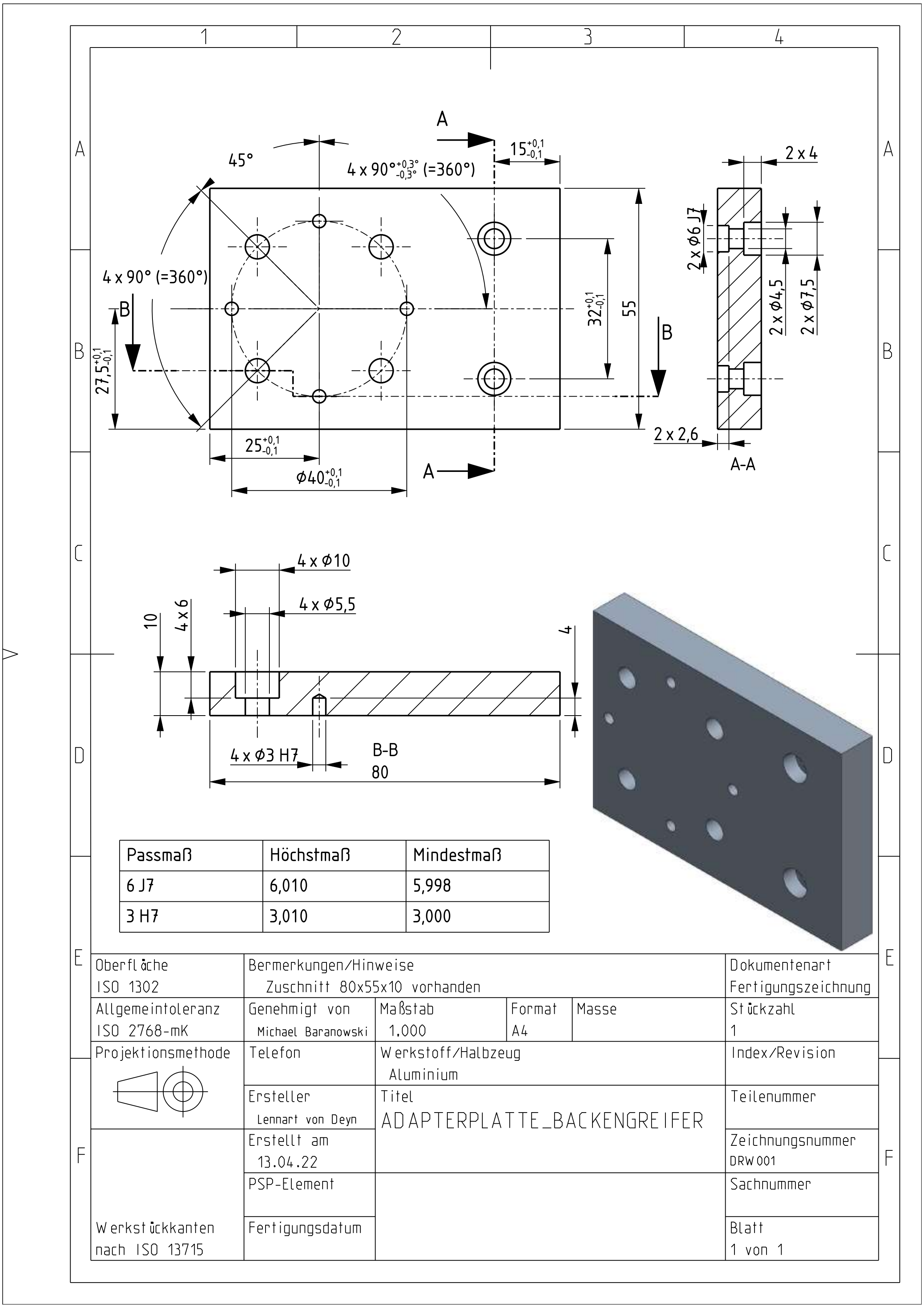


Figure B1: Drawing adapter plate passive module



Passmaß	Höchstmaß	Mindestmaß
6 J7	6,010	5,998
3 H7	3,010	3,000

Figure B2: Drawing adapter plate jaw gripper

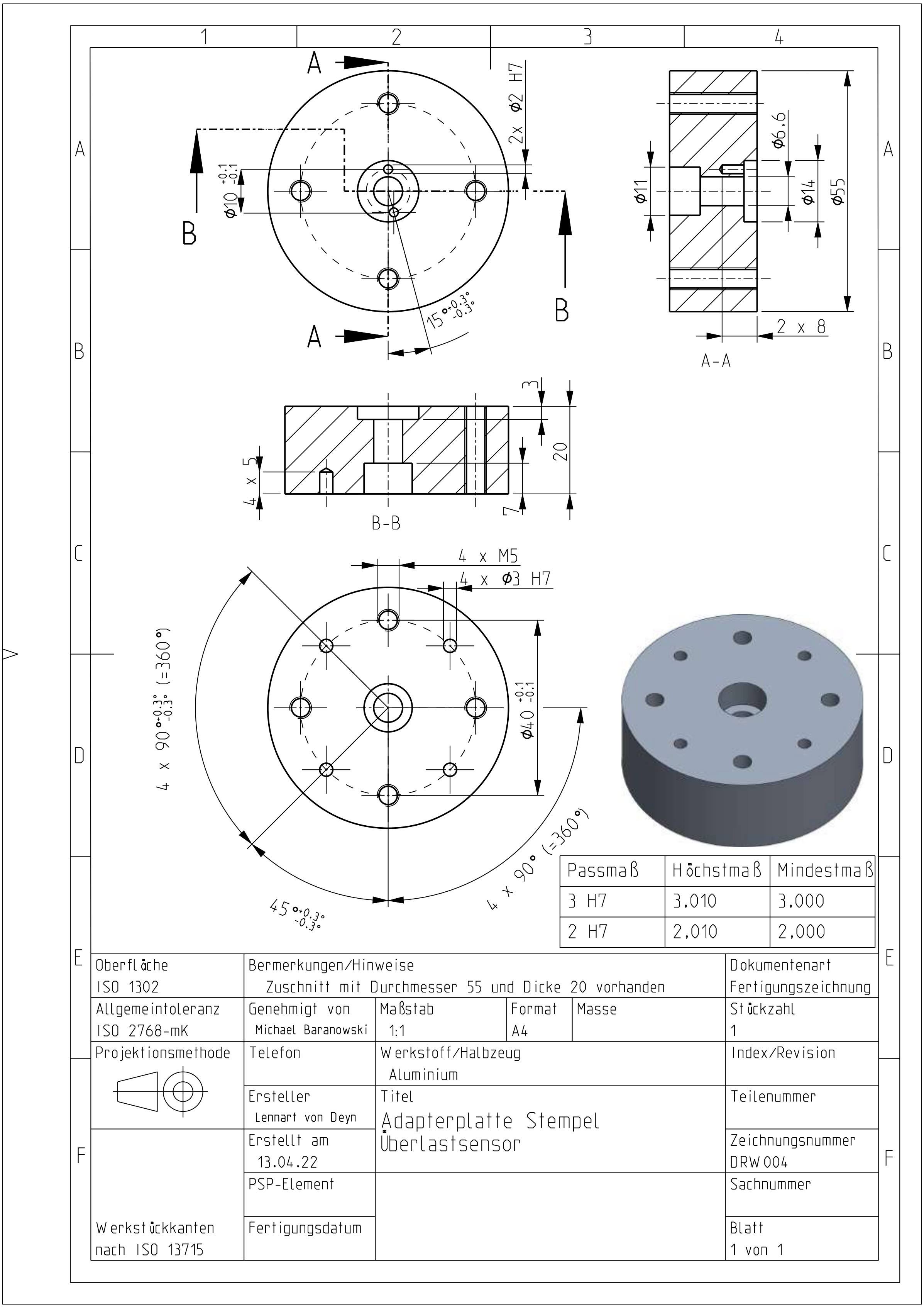


Figure B3: Drawing optional adapter plate overload sensor to end-effector

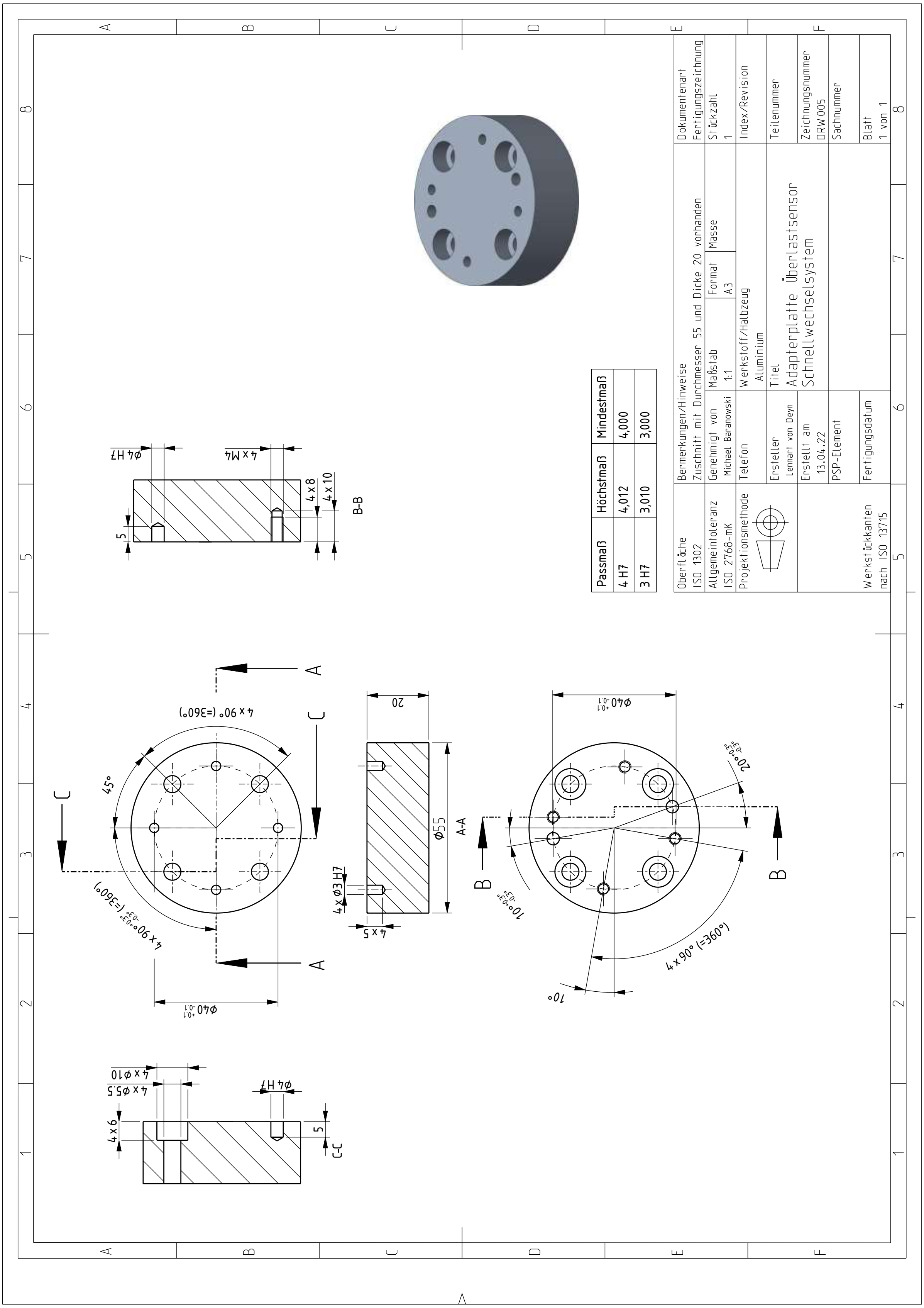


Figure B4: Drawing optional adapter plate quick change system to overload sensor

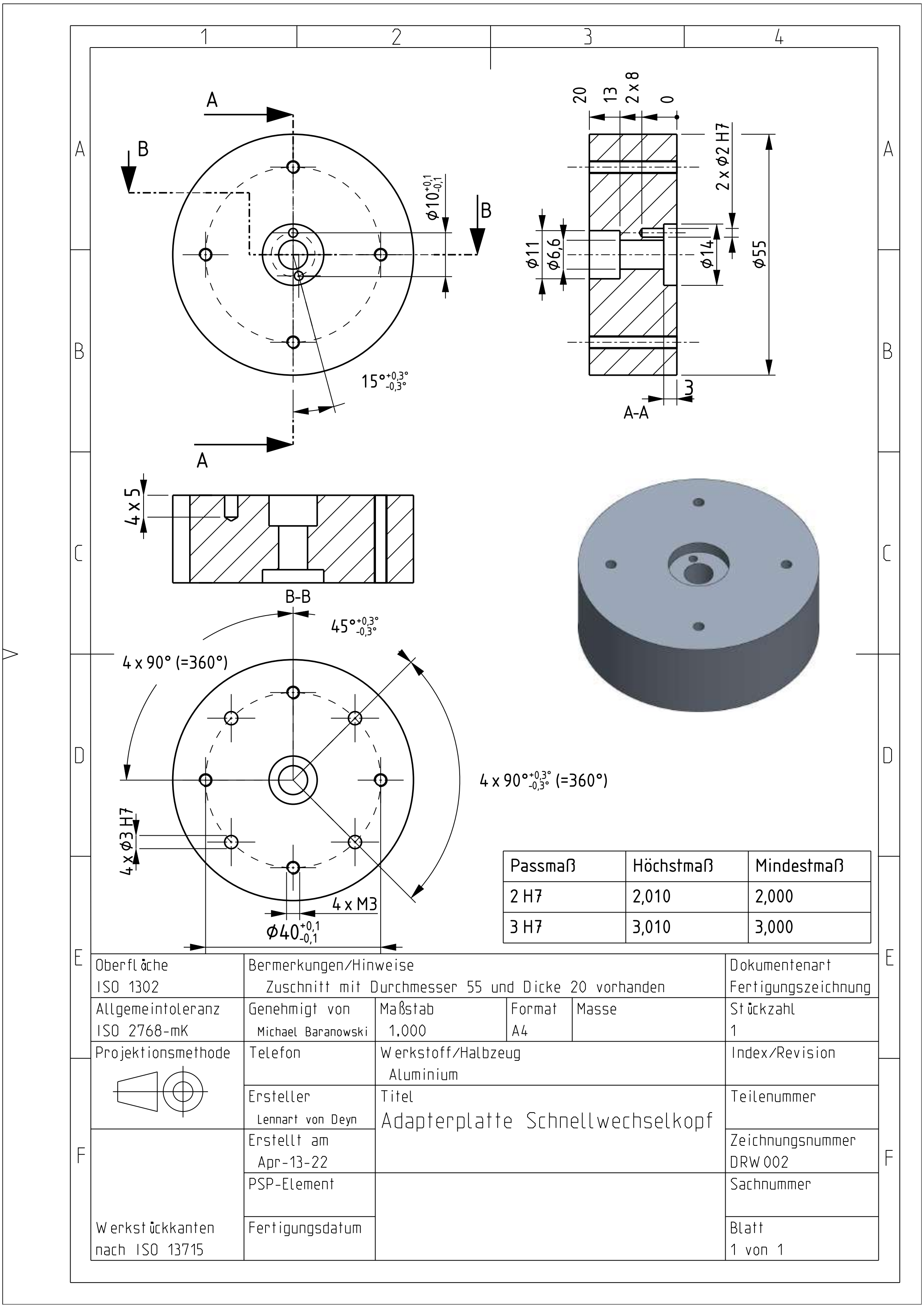


Figure B5: Drawing adapter plate quick change system

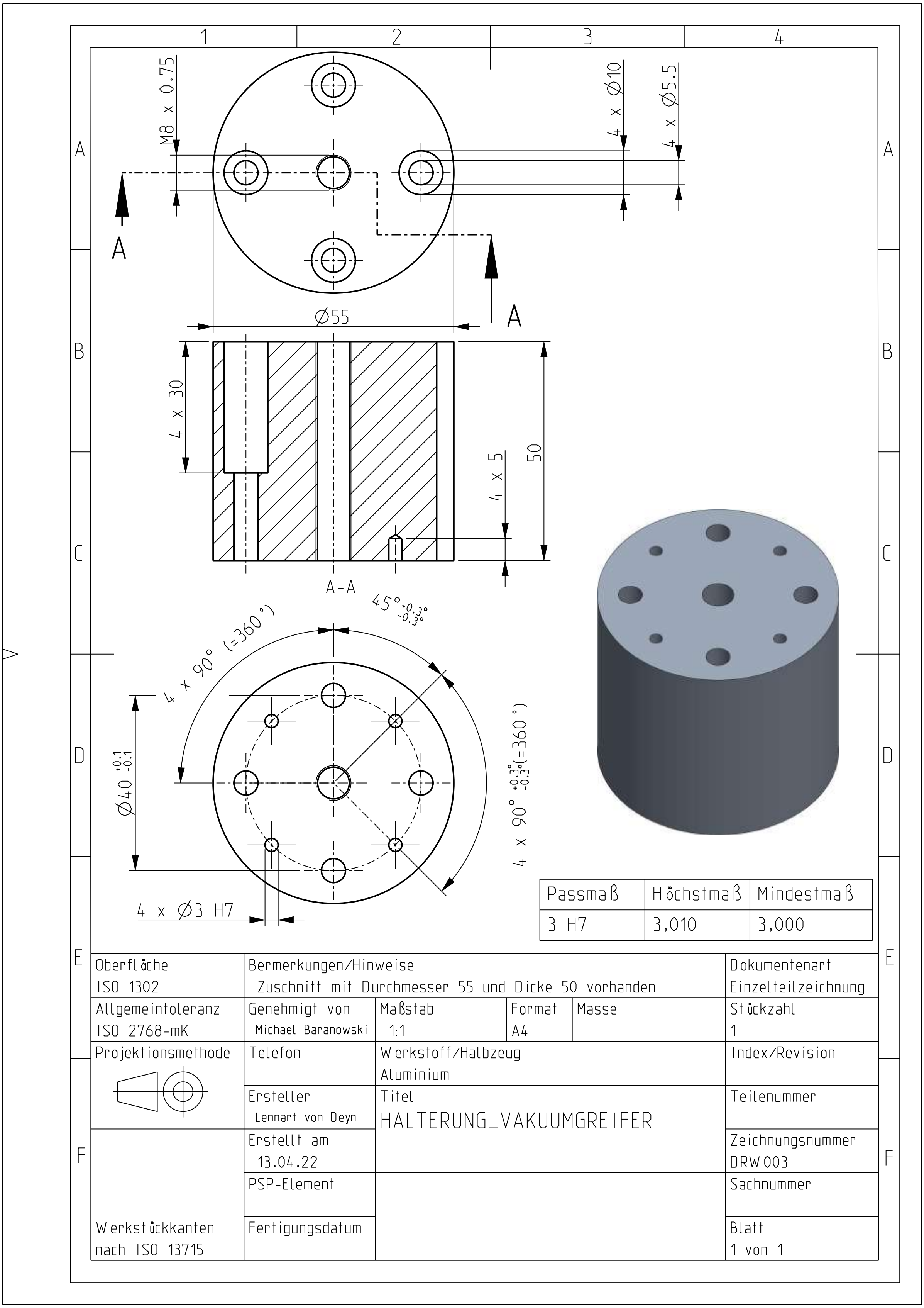


Figure B6: Drawing vacuum gripper mount

Robot Data and Code

Table C.1: Data of coordinate Systems of storage shelf and optimisation component

	X-Coordinate [mm]	Y-Coordinate [mm]	Z-Coordinate [mm]
Storage shelf	319.46	-547.93	6
Optimisation component	39.79	-680.89	16
	A [°]	B [°]	C [°]
Storage shelf	-179.82	0	180
Optimisation component	90.07	0	180

Table C.2: Coordinates of quick change system

	X-Coordinate [mm]	Y-Coordinate [mm]	Z-Coordinate [mm]	A [°]	B[°]	C [°]
Thread effector	-119.22	-727.15	546.88	86.98	0.41	179.84
Second effector	156.02	-724.6	604.57	86.23	0.05	-179.89

Table C.3: Results of the TCP measurement and data of thread effector

X-Coordinate [mm]	Y-Coordinate [mm]	Z-Coordinate [mm]	A [°]	B [°]	C [°]
-4.34	-61.05	179.71	0	0	0
X-Coordinate (COG) [mm]	Y-Coordinate (COG) [mm]	Z-Coordinate (COG) [mm]	A (MIA) [°]	B (MIA) [°]	C (MIA) [°]
-6.4	3.34	106.54	-118.21	-84.29	-113.34
JX [$\mathrm{kg\,m^2}$]	JY [$\mathrm{kg\,m^2}$]	JZ [$\mathrm{kg\,m^2}$]	Mass [kg]	Error	
0.0024	0.0094	0.0099	1.77	0.24	

Table C.4: Results of the TCP measurement and data of jaw gripper

X-Coordinate [mm]	Y-Coordinate [mm]	Z-Coordinate [mm]	A [°]	B [°]	C [°]
38.58	-3.19	196.35	0	0	0
X-Coordinate (COG) [mm]	Y-Coordinate (COG) [mm]	Z-Coordinate (COG) [mm]	A (MIA) [°]	B (MIA) [°]	C (MIA) [°]
6.54	0.43	116.42	-90.64	0	-71.9
JX $[\mathrm{kg\,m^2}]$	JY $[\mathrm{kg\,m^2}]$	JZ $[\mathrm{kg\,m^2}]$	Mass $[\mathrm{kg}]$	Error	
0.0015	0.005	0.0061	1.32	0.41	

Table C.5: Results of the TCP measurement and data of vacuum gripper

X-Coordinate [mm]	Y-Coordinate [mm]	Z-Coordinate [mm]	A [°]	B [°]	C [°]
-1.19	0.5	205.9	0	0	0
X-Coordinate (COG) [mm]	Y-Coordinate (COG) [mm]	Z-Coordinate (COG) [mm]	A (MIA) [°]	B (MIA) [°]	C (MIA) [°]
-12.6	0	100.41	-89.77	0.45	-96.22
JX $[\mathrm{kg\,m^2}]$	JY $[\mathrm{kg\,m^2}]$	JZ $[\mathrm{kg\,m^2}]$	Mass $[\mathrm{kg}]$	Error	
0.0009	0.0033	0.0037	1.04	0.4	

Listing C.1: Robot code to get thread effector from quick change system

```
DEF SWS_Back_ThreadEff( )
;FOLD SPTP Keine_Kollision CONT Vel=10 % PDAT8 Tool[6]:Gewinde-
   Effektor Base[0]  ;%{PE}
;FOLD SPTP Prepos_SWS CONT Vel=10 % PDAT2 Tool[6]:Gewinde-
   Effektor Base[0]  ;%{PE}
;FOLD SPTP Top_SWS_Gewindeffektor Vel=10 % PDAT1 Tool[6]:Gewinde-
   Effektor Base[0]  ;%{PE}
;FOLD SLIN SWS_Gewindeffektor Vel=0.01 m/s CPDAT1 Tool[6]:Gewinde
   -Effektor Base[0]  ;%{PE}

;Valve control
;FOLD OUT 1 'Ventil 2A-SWS Zu' State=False  ;%{PE}
;FOLD OUT 2 'Ventil 2B-SWS Auf' State=True  ;%{PE}
;FOLD WAIT Time= 0.5 sec ;%{PE}
;FOLD OUT 2 'Ventil 2B-SWS Auf' State=False  ;%{PE}

;FOLD SLIN Top_SWS_Gewindeffektor Vel=0.02 m/s CPDAT2 Tool[6]:
   Gewinde-Effektor Base[0]  ;%{PE}
;FOLD SPTP Prepos_SWS CONT Vel=10 % PDAT4 Tool[6]:Gewinde-
   Effektor Base[0]  ;%{PE}
;FOLD SPTP Keine_Kollision CONT Vel=10 % PDAT9 Tool[6]:Gewinde-
   Effektor Base[0]  ;%{PE}

;FOLD SPTP HOME Vel=10 % DEFAULT ;%{PE}
END
```

Listing C.2: Robot code for all installation processes

```
DEF Master( )
DECL INT Correction_Z
DECL INT M6Count
DECL INT M5Count
DECL INT M4Count
DECL INT M3Count
DECL INT Effektor
DECL INT Insertnumber
DECL E6POS XIntegration
;FOLD INI;%{PE}
```

```

;Declaration
Insertnumber=0
M6Count=0
M5Count=0
M4Count=0
M3Count=0

;1:Thread,2:Vakuum,3:Jaw gripper
Effektor=1

Correction_Z = 1.5

;Reset of outputs
;FOLD OUT 11 ’Vacuum’ State=False  ;%{PE}
;FOLD OUT 21 ’RobotClear’ State=True  ;%{PE}
;FOLD OUT 3 ’Ventil 1A-Greifer Zu’ State=False  ;%{PE}
;FOLD OUT 4 ’Ventil 1B-Greifer Auf’ State=True  ;%{PE}
;FOLD WAIT Time= 0.1 sec ;%{PE}
;FOLD OUT 4 ’Ventil 1B-Greifer Auf’ State=False  ;%{PE}
;FOLD OUT 20 ’startInsert’ State=False  ;%{PE}
;FOLD OUT 21 ’RobotClear’ State=False  ;%{PE}
;FOLD OUT 36 ’insertRequest’ State=False  ;%{PE}
;FOLD OUT 37 ’xRequest’ State=False  ;%{PE}
;FOLD OUT 38 ’yRequest’ State=False  ;%{PE}
;FOLD OUT 39 ’zRequest’ State=False  ;%{PE}

;Move to start position
;FOLD SPTP Prepos_Aufnahme Vel=5 % PDAT21 Tool[6]:Gewinde-Effektor Base[0]  ;%{PE}

;While loop without condition
WHILE True

;Reset of Robotclear after each installation process
;FOLD OUT 21 ’RobotClear’ State=False  ;%{PE}

;Reacts to M113 setting input 32 true and returns effectors
IF  ( $IN[32]== TRUE ) THEN
```

```

   IF Effektor ==1 THEN
      SWS_Back_ThreadEff( )
      Effektor = 0
   ENDIF


   IF  Effektor == 2 THEN
      SWS_Back_Vakuum( )
      Effektor = 0
   ENDIF
ENDIF

;Get data from PLC
Insertnumber = getInsertFromPLC()
XIntegration = getPointFromPLC()

;If the incorrect effector is equipped, change effector
IF (Insertnumber >=3) AND (Insertnumber<=6) THEN

   IF  (Effektor == 2) OR (Effektor == 3) THEN
      SWS_Back_Vakuum( )
      Effektor=0
   ENDIF

   IF Effektor == 0 THEN
      SWS_Get_ThreadEff( )
      Effektor=1
   ENDIF

ENDIF


IF (Insertnumber ==8) OR (Insertnumber==10) THEN

   IF  (Effektor == 1) THEN
      SWS_Back_ThreadEff( )
      Effektor=0
   ENDIF
```

```
   IF Effektor == 0 THEN
      SWS_Get_Vakuum( )
      Effektor=2
   ENDIF

ENDIF

;Declaration of parameters for each type of threaded insert
IF  Insertnumber==3 THEN
   XPickup.X=110
   XPickup.Y=21.5+M3Count*15
   XPickup.Z=-2.5

   XTop_Pickup.X=110
   XTOP_Pickup.Y=20+M3Count*15
   XTOP_Pickup.Z=-2.5-10

   XThread_Int.Z = XIntegration.Z +0.9+Correction_Z

   XTop_Thread_Int.Z = XIntegration.Z + 10.9 +Correction_Z


   M3Count=M3Count + 1


ENDIF

IF  Insertnumber==4 THEN
   XPickup.X=75
   XPickup.Y=20.5+M4Count*15
   XPickup.Z=-9.1

   XTop_Pickup.X=75
   XTOP_Pickup.Y=20.5+M4Count*15
   XTOP_Pickup.Z=-9.1-10

   XThread_Int.Z = XIntegration.Z +2.2 +Correction_Z

```

```
   XTop_Thread_Int.Z = XIntegration.Z + 12.2 + Correction_Z
   M4Count=M4Count + 1
ENDIF
IF  Insertnumber==5 THEN
   XPickup.X=40
   XPickup.Y=21.5+M5Count*15
   XPickup.Z=-15.5
   XTop_Pickup.X=40
   XTOP_Pickup.Y=21.5+M5Count*15
   XTOP_Pickup.Z=-15.5-10
   XThread_Int.Z = XIntegration.Z +3.5 + Correction_Z
   XTop_Thread_Int.Z = XIntegration.Z + 13.5 + Correction_Z
   M5Count=M5Count + 1
ENDIF
IF  Insertnumber==6 THEN
   XPickup.X=0
   XPickup.Y=21.5+M6Count*15
   XPickup.Z=-23.7
   XTop_Pickup.X=0
   XTOP_Pickup.Y=21.5+M6Count*15
   XTOP_Pickup.Z=-23.7-10
   XThread_Int.Z = XIntegration.Z +5.2+Correction_Z
   XTop_Thread_Int.Z = XIntegration.Z + 15.2+Correction_Z
   M6Count=M6Count + 1
```

```


ENDIF

;Integration process for threaded inserts
IF (Insertnumber >=3) AND (Insertnumber<=6) THEN

;Declaration of integration coordinates
   XTop_Thread_Int.X = XIntegration.X
   XTop_Thread_Int.Y = XIntegration.Y

   XThread_Int.X = XIntegration.X
   XThread_Int.Y = XIntegration.Y

   XThread_Int_Final.X = XIntegration.X + 0.8
   XThread_Int_Final.Y = XIntegration.Y -0.3
   XThread_Int_Final.Z = XThread_Int.Z


;FOLD SPTP Prepos_Aufnahme Vel=5 % PDAT1 Tool[6]:Gewinde-Effektor Base[0]  ;%{PE}
;FOLD SPTP Top_Pickup Vel=3 % PDAT2 Tool[6]:Gewinde-Effektor Base[6]:Gewinde_Ablage  ;%{PE}
;FOLD SLIN Pickup Vel=0.02 m/s CPDAT1 Tool[6]:Gewinde-Effektor Base[6]:Gewinde_Ablage  ;%{PE}

;Activates jaw gripper
;FOLD OUT 3 'Ventil 1A-Greifer Zu' State=True  ;%{PE}

;FOLD SLIN Top_Pickup Vel=0.02 m/s CPDAT2 Tool[6]:Gewinde-Effektor Base[6]:Gewinde_Ablage  ;%{PE}
;FOLD SPTP Collision_Prev Vel=5 % PDAT12 Tool[6]:Gewinde-Effektor Base[0]  ;%{PE}
;FOLD SLIN Door Vel=0.2 m/s CPDAT5 Tool[6]:Gewinde-Effektor Base[0]  ;%{PE}

;FOLD WAIT FOR ( IN 30 'allClear' )  ;%{PE}


```

```
;FOLD SLIN Top_Thread_Int Vel=0.2 m/s CPDAT13 Tool[6]:Gewinde-Effektor Base[1]:Druckbett  ;%{PE}
;FOLD SLIN Thread_Int Vel=0.02 m/s CPDAT3 Tool[6]:Gewinde-Effektor Base[1]:Druckbett  ;%{PE}

;Release of insert
;FOLD OUT 3 'Ventil 1A-Greifer Zu' State=False  ;%{PE}
;FOLD OUT 4 'Ventil 1B-Greifer Auf' State=True  ;%{PE}
;FOLD WAIT Time= 0.1 sec ;%{PE}
;FOLD OUT 4 'Ventil 1B-Greifer Auf' State=False  ;%{PE}

;FOLD SLIN Thread_Int_Final Vel=0.005 m/s CPDAT14 Tool[6]:Gewinde-Effektor Base[1]:Druckbett  ;%{PE}

;PLC communication to start installation and wait till complete
;FOLD OUT 20 'startInsert' State=True  ;%{PE}
;FOLD WAIT Time= 0.1 sec ;%{PE}
;FOLD WAIT FOR ( IN 31 'InsertDone' )  ;%{PE}
;FOLD OUT 20 'startInsert' State=False  ;%{PE}


;FOLD SLIN Top_Thread_Int Vel=0.02 m/s CPDAT4 Tool[6]:Gewinde-Effektor Base[1]:Druckbett  ;%{PE}
;FOLD SPTP Door Vel=5 % PDAT9 Tool[6]:Gewinde-Effektor Base[0] ;%{PE}
;FOLD SLIN Collision_Prev Vel=0.2 m/s CPDAT6 Tool[6]:Gewinde-Effektor Base[0]  ;%{PE}
;FOLD SPTP Prepos_Aufnahme Vel=5 % PDAT10 Tool[6]:Gewinde-Effektor Base[0]  ;%{PE}

;Report that robot left printing chamber
;FOLD OUT 21 'RobotClear' State=True  ;%{PE}
;FOLD WAIT Time= 0.1 sec ;%{PE}
ENDIF

;Integration with vacuum gripper
IF  Insertnumber == 8 THEN
   XInt.X = XIntegration.X
   XInt.Y = XIntegration.Y
```

```
    XInt.Z = XIntegration.Z
    XTop_Int.X = XIntegration.X
    XTop_Int.Y = XIntegration.Y
    XTop_Int.Z = XIntegration.Z +15
;FOLD SPTP PrePos_Vacuum Vel=5 % PDAT26 Tool[1]:Backengreifer Base[0] ;%{PE}
;FOLD SPTP Top_Board_1 Vel=5 % PDAT28 Tool[2]:Vakuumgreifer Base[0]  ;%{PE}
;FOLD SLIN Board_1 Vel=0.01 m/s CPDAT15 Tool[2]:Vakuumgreifer Base[0]  ;%{PE}
;FOLD OUT 11 'Vacuum' State=True  ;%{PE}
;FOLD WAIT Time= 1.0 sec ;%{PE}
;FOLD SLIN Top_Board_1 Vel=0.02 m/s PDAT28 Tool[2]:Vakuumgreifer Base[0]  ;%{PE}
;FOLD SPTP PrePos_Vacuum Vel=5 % PDAT27 Tool[1]:Backengreifer Base[0] ;%{PE}
;FOLD SPTP HOME Vel=5 % DEFAULT ;%{PE}
;FOLD WAIT FOR ( IN 30 'allClear' )  ;%{PE}
;FOLD SLIN Top_Int Vel=0.2 m/s CPDAT19 Tool[2]:Vakuumgreifer Base[1]:Druckbett  ;%{PE}
;FOLD SLIN Int Vel=0.01 m/s CPDAT17 Tool[2]:Vakuumgreifer Base[1]:Druckbett  ;%{PE}
;FOLD OUT 11 'Vacuum' State=False  ;%{PE}
;FOLD WAIT Time= 1.0 sec ;%{PE}
;FOLD SLIN Top_Int Vel=0.02 m/s CPDAT18 Tool[2]:Vakuumgreifer Base[1]:Druckbett  ;%{PE}
;FOLD SPTP HOME Vel=5 % DEFAULT ;%{PE}
;FOLD SPTP PrePos_Vacuum Vel=5 % PDAT29 Tool[1]:Backengreifer Base[0] ;%{PE}
```

```
;Report that robot left printing chamber
;FOLD OUT 20 'startInsert' State=True  ;%{PE}
;FOLD WAIT Time= 0.1 sec ;%{PE}
;FOLD OUT 20 'startInsert' State=False  ;%{PE}
;FOLD OUT 21 'RobotClear' State=True  ;%{PE}
;FOLD WAIT Time= 0.1 sec ;%{PE}

ENDIF


;Integration with jaw gripper
IF  Insertnumber == 10 THEN
   XWasher_Int.X = XIntegration.X
   XWasher_Int.Y = XIntegration.Y
   XWasher_Int.Z = XIntegration.Z+1

   XTop_Washer_Int.X = XIntegration.X
   XTop_Washer_Int.Y = XIntegration.Y
   XTop_Washer_Int.Z = XIntegration.Z +15

;FOLD OUT 3 'Ventil 1A-Greifer Zu' State=True  ;%{PE}
;FOLD WAIT Time= 0.1 sec ;%{PE}
;FOLD OUT 3 'Ventil 1A-Greifer Zu' State=False  ;%{PE}

;FOLD SPTP PrePos_Washer Vel=5 % PDAT30 Tool[1]:Backengreifer Base[0]  ;%{PE}
;FOLD SPTP Top_Washer_1 Vel=5 % PDAT31 Tool[1]:Backengreifer Base[0]  ;%{PE}
;FOLD SLIN Washer_1 Vel=0.01 m/s CPDAT20 Tool[1]:Backengreifer Base[0]  ;%{PE}

;FOLD OUT 4 'Ventil 1B-Greifer Auf' State=True  ;%{PE}
;FOLD WAIT Time= 0.5 sec ;%{PE}

;FOLD SLIN Top_Washer_1 Vel=0.02 m/s CPDAT22 Tool[1]:Backengreifer Base[0]  ;%{PE}
;FOLD SPTP PrePos_Washer Vel=5 % PDAT34 Tool[1]:Backengreifer Base[0]  ;%{PE}
;FOLD SPTP HOME Vel=5 % DEFAULT ;%{PE}
```

```

;FOLD WAIT FOR ( IN 30 'allClear' ) ;%{PE}

;FOLD SLIN Top_Washer_Int Vel=0.2 m/s CPDAT23 Tool[1]:
    Backengreifer Base[1]:Druckbett ;%{PE}
;FOLD SLIN Washer_Int Vel=0.01 m/s CPDAT24 Tool[1]:Backengreifer
    Base[1]:Druckbett ;%{PE}

;FOLD OUT 4 'Ventil 1B-Greifer Auf' State=False ;%{PE}
;FOLD OUT 3 'Ventil 1A-Greifer Zu' State=True ;%{PE}
;FOLD WAIT Time= 0.1 sec ;%{PE}
;FOLD OUT 3 'Ventil 1A-Greifer Zu' State=False ;%{PE}

;FOLD SLIN Top_Washer_Int Vel=0.02 m/s CPDAT25 Tool[1]:
    Backengreifer Base[1]:Druckbett ;%{PE}
;FOLD SPTP HOME Vel=5 % DEFAULT ;%{PE}
;FOLD SPTP PrePos_Washer Vel=5 % PDAT35 Tool[1]:Backengreifer
    Base[0] ;%{PE}

;Report that robot left printing chamber
;FOLD OUT 20 'startInsert' State=True ;%{PE}
;FOLD WAIT Time= 0.1 sec ;%{PE}
;FOLD OUT 20 'startInsert' State=False ;%{PE}
;FOLD OUT 21 'RobotClear' State=True ;%{PE}
;FOLD WAIT Time= 0.1 sec ;%{PE}
ENDIF

ENDWHILE
END
```

Listing C.3: Robot code for data transfer

```
DEFFCT INT getInsertFromPLC( )
DECL INT Error
DECL INT Insertnumber

Insertnumber = 0
Error=0

;FOLD OUT 36 ’insertRequest’ State=True  ;%{PE}
;FOLD Parameters ;%{h}
;FOLD WAIT FOR ( IN 36 ’InsertReady’ )  ;%{PE}
;Wait for PLC
;FOLD WAIT Time= 0.1 sec ;%{PE}

   ;read Insertvlue
   Insertnumber = commValue() / 100.0

   ;confirm Insertvalue, if value is in range
   IF (Insertnumber < 1) OR (Insertnumber > 16) THEN
         Error = Error+1
   ENDIF

;FOLD OUT 36 ’insertRequest’ State=False  ;%{PE}

IF  Error > 0 THEN
;FOLD OUT 41 ’errorFlag’ State=True  ;%{PE}
ENDIF
   RETURN(Insertnumber)
ENDFCT
```