Development of a Modular CNC-Cell for Robot-Assisted Milling and 3D-Printing

Mathias Prast, B.Sc., Benjamin Massow, B.Sc., M.Sc. (Supervisor)

***Abstract*—While industrial robots have become ubiquitous in manufacturing for repetitive tasks like welding and painting, their potential in shaping operations remains largely unexploited. This underutilization is surprising considering the unique advantages robots offer, for example, in additive manufacturing processes due to their multiple degrees of freedom. This thesis explores robotic machining and robotic additive manufacturing. One key obstacle of robotic machining is the high cost and proprietary nature of robot-specific tools. Post-processors for such complex systems are rare, expensive, and come with a high additional computational cost. To address these limitations, this thesis develops a demonstrator platform that integrates additive manufacturing and milling capabilities with a robotic arm for CNC machining. In order to optimize the available space, an existing demonstrator platform, which was designed in a preceding thesis [1], is redesigned to accommodate a heatbed for additive manufacturing and an extraction system in order to remove chips produced during the milling process. A 3D-print head with the desired characteristics is chosen, and the print head and a milling spindle are connected to the robot. The external rotating table is connected and implemented on the robot. A crucial objective of this research is the development of a user-friendly tool chain for generating reliable CAM programs. Different CAM environments and post-processors are evaluated and compared to optimize the tool chain for generating efficient robotic tool paths.**

***Keywords*—Industrial Robots, KUKA, Robotic Additive Manufacturing, Robotic Milling**

I. Introduction

A. Motivation

INDUSTRIAL robots are an integral part in today's manufacturing environment due to their versatility and their ability to perform repetitive and unpleasant tasks with high efficiency and productivity. Their main tasks are welding, painting, pick and place operations, packaging and material handling.

Nearly 2.7 million industrial robots are operating in factories worldwide [2]. Currently, less than 5% [3] of all sold robots are used in material shaping processes. This statistic is expected to change in the future as manufacturing shifts from mass production to more customized production across various product types. Robots will increasingly be required to undertake material shaping processes, like milling and additive manufacturing, thanks to their high versatility and multiple degrees of freedom. Despite these advantages, several drawbacks explain why industrial robots have not yet replaced computer numerical control (CNC) machines in material shaping. Due to their serial axis design, where joints are connected by rigid links, industrial robots have a stiffness approximately 50 times lower than Cartesian machines [4], resulting in a higher likelihood of chatter when machining hard materials.

The most significant drawback is the increased complexity in manufacturing processes with the addition of multiple axes. Path planning and programming for these complex manufacturing steps are more challenging, necessitating specialized Computer-Aided Manufacturing (CAM) systems capable of generating robotic paths.

B. Objective

This thesis aims to finalize the design and manufacturing of the in [1] designed demonstration platform. The KUKA KR10 R900-2 industrial robot, its add-ons, and its rotating table are set up so that the cell can be used for manufacturing processes. Additionally, several parts of the cell, such as the doors and the machine covers, are manufactured and assembled.

A main goal of this research is to evaluate different CAM systems and their postprocessors. Additionally, a broadly available postprocessor for regular CNC machines is adapted for robotic applications. The most suitable CAM system results in a toolchain that is documented to communicate the difficulties and workflows coherent with robotic manufacturing for potential users.

To test the robotic manufacturing capabilities of the CAM systems for milling, a variable-frequency-drive (VFD) is implemented on the robot to drive the main spindle. This setup is then used to identify and address weaknesses within the robot cell compared to regular cutting machines.

For additive manufacturing, a high-flow Fused Deposition Modeling (FDM) extruder is implemented onto the robot. Additionally, a heatbed is added to the rotating table, which requires a complete redesign of the table and the extraction system. User-specific M-codes are implemented on the robot to control the temperatures.

II. State of the Art

A. Robotic Assisted Milling

Milling is a high material removal rate operation that demands high machining and surface quality to meet industrial standards [5]. This process is critical in various manufacturing applications, requiring both accuracy and efficiency to produce high-quality components.

Regular cutting machines still prevail over robot-assisted manufacturing in current times. The underlying issues that hinder robotic-assisted milling use cases are mainly caused by their low stiffness.

Due to the layout of an industrial robot, even small deviations in one of the first axes have a high impact on the Tool Center Point (TCP) position. Robots differentiate from regular cutting machines regarding the Cartesian stiffness, which varies with different configurations and joint positions [6]. A further major drawback regarding the accuracy of an industrial robot is due to gear backlash [5], which describes the slight play between gears within the gearboxes of the robot when the axis direction is reversed.

Working area is one of the main strengths of robot-assisted milling. Already relatively small and inexpensive robots have big working areas. Positioners are used to further extend the operating range of industrial robots. These positioners enhance the flexibility and accessibility of the robotic system, allowing for more complex and precise operations.

1) Cutting forces: The interaction between the cutting tool and the workpiece during the milling process is critical, as the resulting forces influence the efficiency of material removal and the quality of the machined surface. These overall forces result in a waveform, highlighted in Figure 1, with a cyclic pattern, corresponding to the periodic engagement and disengagement of the cutting edges with the workpiece.

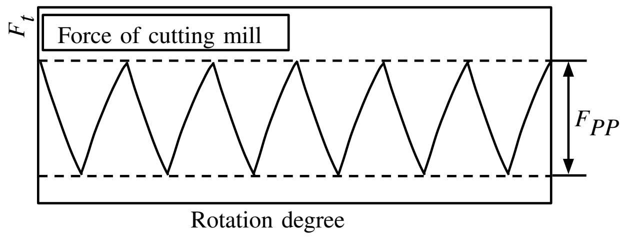

Fig. 1. Depiction of the cutting forces [7].

In robotic machining, the cutting forces must be minimized due to the low stiffness of the industrial robot. This can be achieved using up milling, which generates a lifting force more suitable for machines prone to backlash errors. End mills with differential pitch and unequal helix geometries can be used to reduce harmonic vibrations. Differential pitch cutters have uneven spacing of the cutting edge along the circumference of the tool which results in a reduction of the harmonic vibrations.

B. Robotic Additive Manufacturing

Additive manufacturing (AM) is characterized as a process that involves the deposition of material in successive layers to build a component. While various 3D printing technologies exist, an AM extruder is generally attached to the robot to fabricate the workpiece. This technique is particularly suited for working with softer materials, where the machining requirements are less significant. Consequently, the lower stiffness of the robot, often a limitation in subtractive manufacturing processes, does not significantly impact the quality or precision [5] of the manufacturing process.

While a filament extruder has superior print quality and is able to print complex designs, a pellet extruder is much more cost-efficient. The material cost of pellets is around one-fifth of the filament cost. A pellet extruder has problems with over-extrusion and porosity due to trapped air and moisture present within the pellets [8].

When integrated using an industrial robot, FDM is able to offer a very large build volume. Utilizing the robot's capabilities to manipulate the extruder head orientation, as indicated in Figure 2, no support materials are necessary by the use of non-planar slicing, which enables overhangs of up to 90° [9]. This makes it possible to produce large-scale objects that would otherwise be impractical to manufacture using regular Cartesian-style 3D printers.

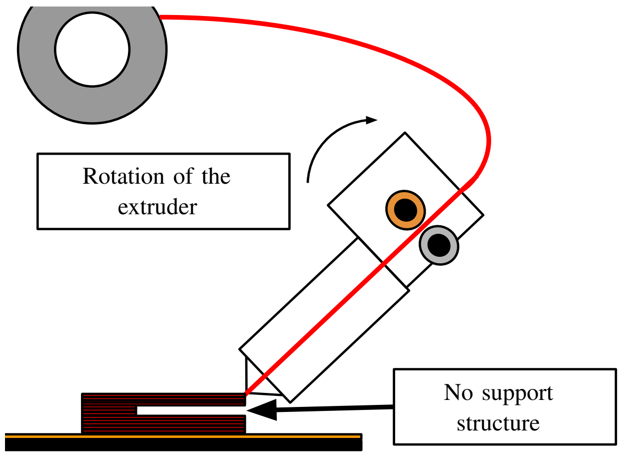

Fig. 2. Depiction of a overhang printed without support using non planar slicing.

C. Robotic Manufacturing Toolchains

1) Application software: Different application software can be used in order to control the robot's path, which can differ greatly in terms of HMI and functions. The most common approach is the description of the machining path by the use of native robot languages like KUKA Robot Language (KRL) or ABB Rapid. This has the advantage that robot operators can easily understand the code. Postprocessors required to translate toolpaths into robotic code are significantly more widespread than other types of robotic postprocessors.

Implementation of a CNC expansion package enables the use of regular CNC code. G-code-based robot programming enables radius compensation directly on the controller. Furthermore, much more precise path performance is possible with the use of such an expansion package. A downside of this approach is that postprocessors are not as widespread as for robotic code.

Implementing a regular CNC controller enables the machine operator to have all CNC specific functions and the programming directly on the machine. Existing postprocessors for the controller can be used, but they have to be adapted in order to represent the desired configuration of the robot.

III. Concept

A. Setup of the Robot

As offline simulation [1] reveals, in order to maximize the available workspace, the robot has to be mounted on the wall. This enables the processing of large workpieces and helps to avoid singularities. Figure 3 showcases the resulting orientation of the robot within the cell.

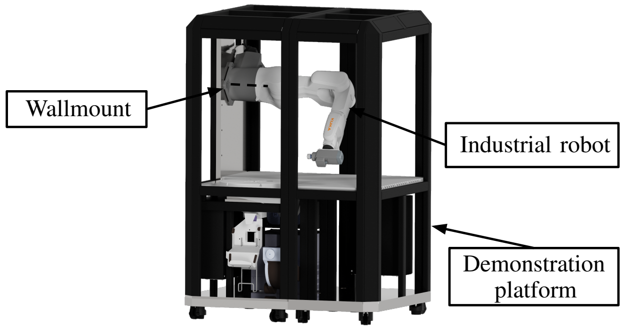

Fig. 3. Orientation of the robot developed in the preceding thesis [1].

To correctly position the world coordinate system, the kinematic base of the robot must be changed [10] within KUKA.WorkVisual. After the installation of KUKA.CNC on the robot controller, it can naively execute NC programs, as seen in figure 4. The code, which is run within KUKA.CNC, is then translated into motion data for the robot using ProConOS [11], which is based on the ISG CNC kernel [12]. The robot and the peripherals, like the milling spindle or the AM extruder, are then connected to the normal operating system KUKA System Software (KSS). To develop these Programmable Logic Controller (PLC) applications, KUKA.PLC Multiprog [13] is used. The addition of a template to ProConOS enables the mapping of I/Os and the development of PLC applications using KUKA.WorkVisual and KUKA.Multiprog.

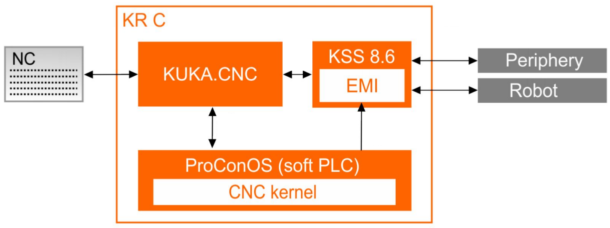

Fig. 4. Overview of a KUKA.CNC based application [11].

B. Rotating Table

A crucial part of robotic manufacturing is the reorientation of the tool. By using a 5-axis vice, as demonstrated in Figure 5, undercuts are made possible. The diameter of the rotating table is enlarged to 500 mm in order to facilitate the vice and larger workpieces. A pancake slip ring is employed in order to enable endless operation of the positioner, while a heatbed for AM is employed.

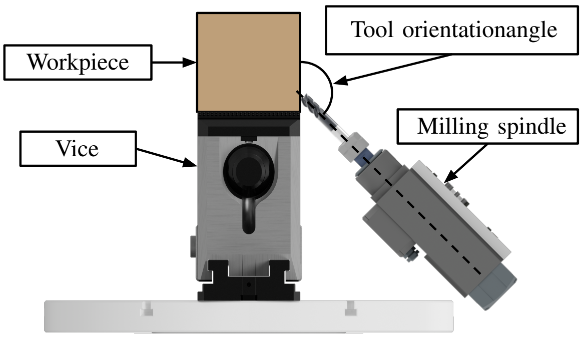

Fig. 5. Possible tool orientation by the use of a 5-axis vice.

The positioner is a BASE kinematic system [14] that moves the workpiece. The axis is directly implemented on the robot as a synchronous and mathematically coupled external A-axis.

C. Implementation of the Milling Spindle

The milling spindle is implemented directly on the robot using ProConOS. A VFD, which drives the spindle, is connected using the EtherCAT adapter FECA-01 [15]. The spindle is run in scalar frequency mode, which does not necessitate the measurement of the actual spindle speed, and a fixed reference is set to enable the precise declaration of the tool length. In order to achieve this, two measurements of the TCP are conducted on the robot, which are depicted in Figure 6. Using the results of these measurements and the corresponding tool lengths, the desired reference TCP is calculated.

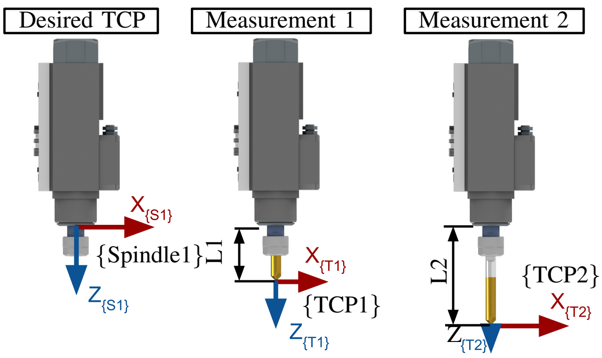

Fig. 6. Calibration of the reference TCP.

D. Additive manufacturing peripherals

Robotic additive manufacturing is not standardized to the same extent as regular 3D printers. Most commercially available solutions make use of an external control unit. These units are usually connected by means of Ethernet/IP interfaces and include stepper motor drivers as well as PID controllers for the heating elements.

The implementation of the AM extruder and all heating elements is possible directly on the robot using ProConOS. All sensors and actuators can be connected using Beckhoff EtherCAT extensions, as shown in figure 7.

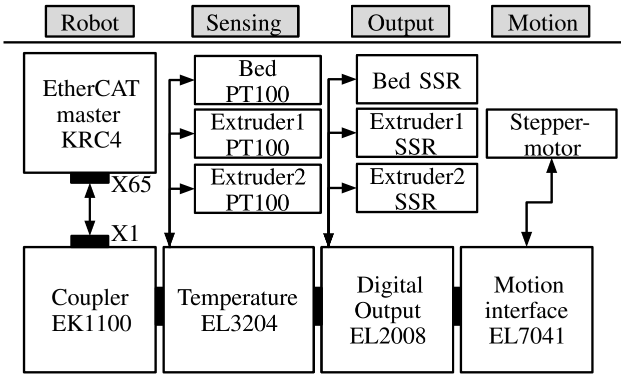

Fig. 7. Implementation of additive manufacturing peripherals on to the robot.

The control structure for both heating elements of the extruder and the heatbed is developed and directly integrated into the robot. In order to simplify the toolchain associated with robotic AM, the corresponding M codes are implemented on the robot.

E. Research and Evaluation of CAM Systems and Postprocessors

To identify the most suitable toolchain for robotic machining, the most common CAM environments are tested. SprutCAM X [16] is a very well established CAM environment for robotic machining that offers postprocessors for KRL and KUKA.CNC. SiemensNX [17], on the other hand, is one of the most widespread CAM systems for regular CNC manufacturing. Only a KRL postprocessor is available, because of which a regular CNC postprocessor is adapted to KUKA.CNC. For both environments, a machine model is developed that incorporates all coordinate systems, tools, and the rotating table.

An evaluation part is designed that incorporates distinct features that are common in robotic machining. This part is then programmed using SiemensNX and SprutCAM in order to compare the complexity and applicability of these toolchains. Evaluation feature 1, indicated in Figure 8, is used to evaluate the capabilities of the postprocessor while face milling circular paths.

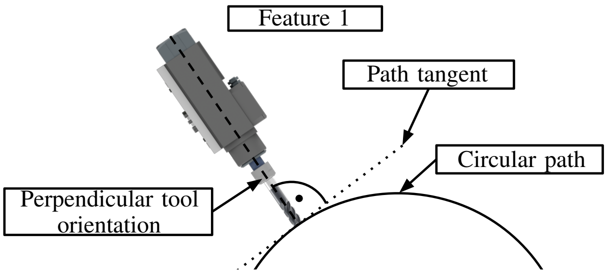

Fig. 8. Evaluation feature 1: Face milling of circular toolpath.

Figure 9 highlights the second evaluation feature, which is the accuracy during pocketing. The inner radius of the part contributes to a larger enlacement of the mill, which results in higher cutting forces that can result in chatter and dimensional errors.

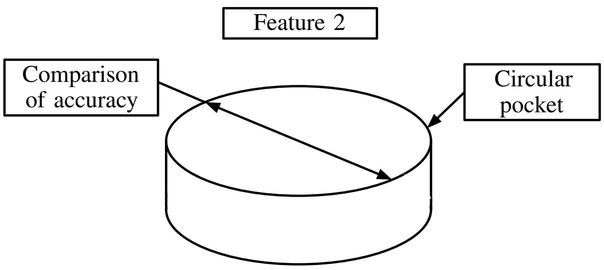

Fig. 9. Evaluation feature 2: Accuracy during pocketing operations.

Feature 3, presented in Figure 10, evaluates the surface quality and accuracy during side milling operations. All features are measured by the use of the ZEISS UPMC 850 Coordinate Measuring Machine (CMM) [18], which ensures reliable and high-quality measurements of the features in order to compare the postprocessors.

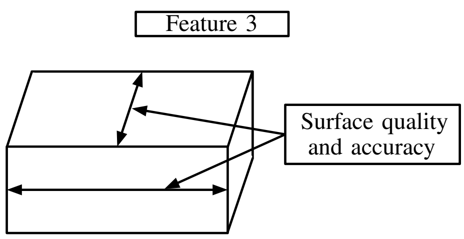

Fig. 10. Evaluation feature 3: Surface quality and accuracy during side milling operations.

IV. Implementation

A. Rotating Table

Figure 11 shows the assembly drawing of the rotating table. A 10 mm high pancake-style slip ring is used for power delivery and temperature sensing of the heatbed. Two XT60 connectors allow quick heat bed connections. The table, made of corrosion-resistant 1.2085 tool steel, features T-slots for fastening workpieces. The positioner is implemented on the robot controller as an External A-Axis System (EASYS) for synchronized control. Calibration involves measuring pin locations at 90° intervals.

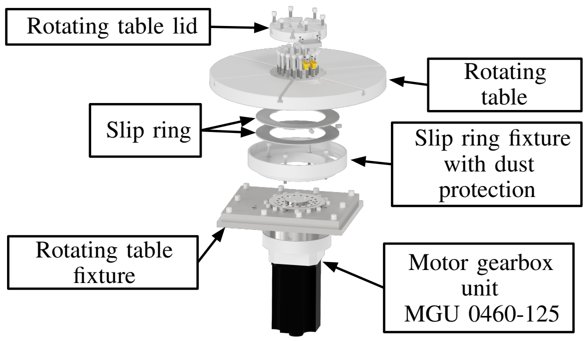

Fig. 11. Assembly drawing of the rotating table.

B. Implementation of Robotic Machining

The milling spindle is integrated directly on the PLC of the robot using a state machine, ensuring no loss of connection during machining. For precise tool calibration, the reference point calibration involves measuring two TCP points on the robot using an NC spot drill. This enables tool management using a presetting device. The coordinate system for milling operations is placed directly on the rotating table, as seen in Figure 12.

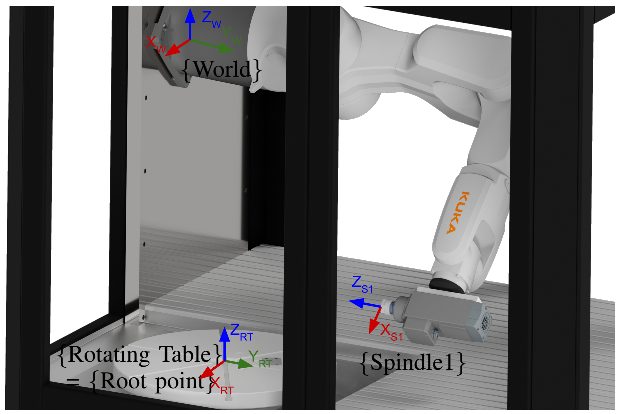

Fig. 12. Coordinate systems used in robotic machining.

C. Implementation of Additive Manufacturing

The additive manufacturing setup integrates a high-flow extruder and a heatbed with the robot, connected via Beckhoff EtherCAT extensions. The extruder is configured as an additional axis in KUKA WorkVisual, with the coordinate system on the heatbed to enable the use of ordinary slicers, as depicted in Figure 13. Temperature control is managed through custom M-codes on the PLC of the robot, ensuring optimal control over the process values by employing a pulse width modulation (PWM) control scheme.

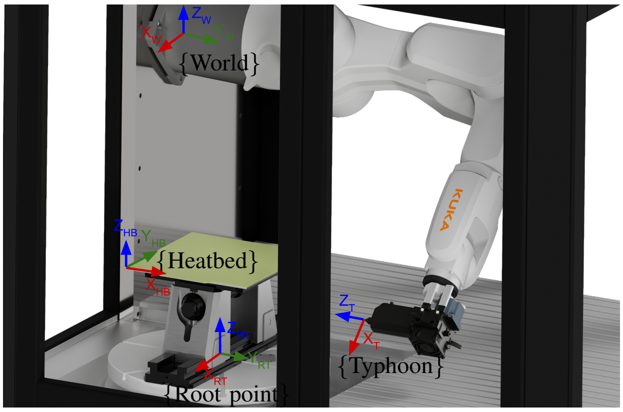

Fig. 13. Coordinate systems used in robotic additive manufacturing.

D. CAM Setup

In Siemens NX, the machine model is developed using the machine tool builder application, importing the computer-aided design (CAD) model of the robot cell. Each joint and motion range are specified, and tools such as the milling spindle and extruder are implemented. SiemensNX lacks a native postprocessor for KUKA.CNC, so an available CNC postprocessor is adapted. This adaptation involves customizing the postprocessor to handle the kinematics and requirements of the robotic cell.

SprutCAM uses the MachineMaker application to create the digital twin of the demonstrator platform. It includes postprocessors for both KRL and KUKA.CNC, facilitating the generation of reliable robotic paths. The environment offers a user-friendly interface, simplifying toolpath generation.

E. Test Setup

The evaluation part, shown in Figure 14, is designed to test the milling capabilities of the robot and the differences between the postprocessors. Features such as circular pockets and various surface finishes are included to assess the performance under different cutting conditions. Different end mills, with varying numbers of cutting edges for both ferrous and non-ferrous metals, are used to determine the impact of cutting forces on the milling process.

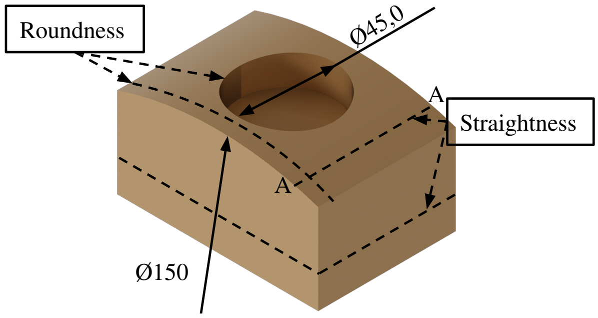

Fig. 14. Depiction of the evaluation part for milling.

The machine's accuracy is assessed using the part outlined in Figure 15 with multiple circular pockets. Each pocket's diameter and centrality are measured to evaluate machine precision and the calibration of the root point.

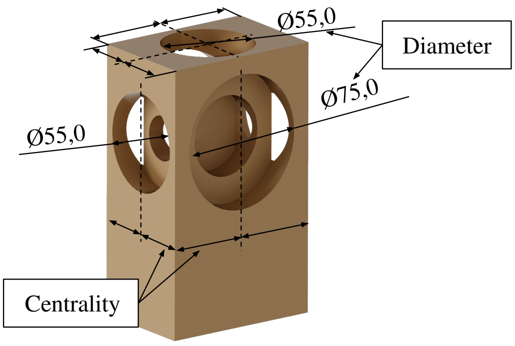

Fig. 15. Depiction of the evaluation part to evaluate the demonstrator platform.

V. Results

A. Evaluation of the CAM Environments

Both SiemensNX and SprutCAM are evaluated for their effectiveness in generating robotic machining paths. SiemensNX offers advanced customization and accurate simulation features, making it ideal for complex operations. However, the adaptation of an existing CNC postprocessor for KUKA.CNC is necessary. SprutCAM provides a more user-friendly interface with reliable postprocessors for KRL and KUKA.CNC, making it suitable for users with varying levels of expertise. Both environments successfully generate accurate tool paths for the evaluation part, but the ease of use and setup in SprutCAM are strong advantages.

B. Evaluation of the Postprocessors

Figure 16 compares the milled pocket with the diameter of 45 mm. It shows that KRL and the utilization of G2/G3 commands for arcs can deliver superior roundness when compared to the rounding of the linear paths.

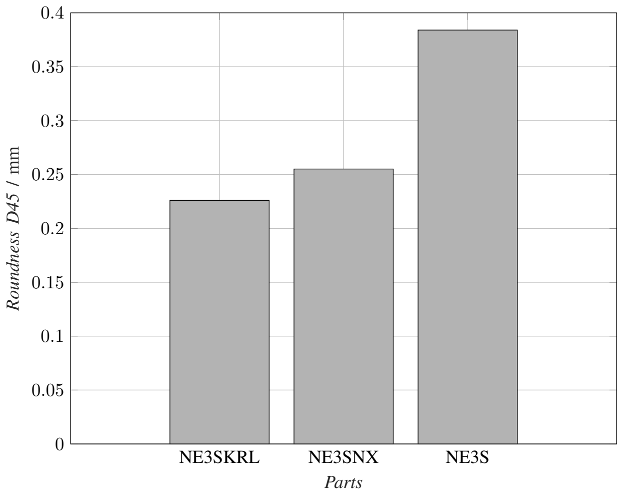

Fig. 16. Comparison of the postprocessors regarding the roundness in the pocket.

C. Evaluation of the Demonstrator Platform

The demonstrator platform's accuracy and stability are evaluated by examining the centrality of the pockets milled into a test part. The pockets on the side faces of the part exhibit a maximum offset of 0.06 mm, indicating a high level of precision and stability in these orientations.

However, the pocket on the top face of the part shows significant deviations, with an offset of up to -1.5 mm in the X direction and -1 mm in the Y direction. These substantial offsets suggest potential issues with the root point orientation of the positioner and tool, leading to uncertainties and inaccuracies when the tool is oriented differently.

D. Milling Results with Varying Process Forces

Cutting forces significantly impact milling accuracy. End mills with more cutting edges produce higher forces and greater dimensional errors. Lower cutting forces generally improve accuracy, though the two-edge end mill is an exception. Reducing cutting forces enhances dimensional accuracy for free-form surfaces but increases deviations in roundness, suggesting tool preload is beneficial during face milling. Straightness is largely unaffected by cutting forces, with higher-force end mills performing better in straightness, supporting the advantage of preload.

E. Additive Manufacturing

The 3D-printer benchmark Benchy [19] is used to evaluate the capabilities of additive manufacturing using the demonstrator platform. The result is shown in Figure 17. The print was done with a layer height of $2\,\mathrm{mm}$ and a line width of $2.5\,\mathrm{mm}$. The robot was able to print the $333\,\mathrm{g}$ part in $26\,\mathrm{min}$. This shows that additive manufacturing on the robot works very well, leveraging the robot's large working area and flexibility. The robot's accuracy is sufficient for additive manufacturing, producing detailed and precise prints.

Fig. 17. Printed evaluation part for additive manufacturing.

VI. Summary and Outlook

A. Summary

This thesis develops a modular CNC cell integrating robot-assisted milling and robotic additive manufacturing. The primary objective is to evaluate these manufacturing techniques and toolchains using an industrial robot, enhancing traditional material shaping with improved flexibility and tool positioning.

A comprehensive review of current robotic-assisted manufacturing techniques evaluates the technology's limitations and advantages. The practical aspect involves developing a demonstrator platform with the KUKA KR 10 R900-2 robot, implementing a milling spindle, and using an extruder for additive manufacturing. An efficient chip extraction system and a heatbed for quick interchangeability between techniques are integrated, along with a rotating table to maximize workspace and facilitate complex tasks.

A significant focus is on creating a user-friendly toolchain for generating reliable CAM programs. Various CAM systems and post-processors are evaluated to determine the best tools for this purpose. Performance tests assess the system's accuracy, repeatability, and efficiency. The results demonstrate the effectiveness of using industrial robots for these tasks, highlighting their potential compared to traditional manufacturing machines.

The combination of milling and additive manufacturing capabilities within a robotic cell showcases the potential for increased flexibility, efficiency, and versatility. By addressing challenges of accuracy, repeatability, and user accessibility, this research contributes to making robotic machining more viable and approachable for industrial applications.

Performance tests demonstrated the system's high accuracy and repeatability in milling operations where cutting forces play a critical role. The results show that lower cutting forces generally improve dimensional accuracy, while tool preload during face milling operations is advantageous in the given configuration of the demonstrator platform. These findings highlight the potential of robotic machining for enhanced flexibility and efficiency in industrial applications.

B. Outlook

Future research will focus on refining the user-friendly toolchain developed in this thesis and integrating control algorithms and sensor feedback to improve precision and reliability. Tests with a broader range of materials, such as aluminium or other metals, will be used to refine milling parameters and evaluate robotic machining of hard materials. Further projects will develop a large-scale robotic manufacturing cell, utilizing methods from this thesis for milling and large-scale additive manufacturing, based on the findings regarding accuracy and versatility.

Integrating non-planar slicing will leverage the robot's multiple degrees of freedom to print complex geometries without support structures. This technique can reduce print time and material usage while improving the mechanical properties of printed objects, showcasing the enhanced capabilities of the robotic CNC cell.

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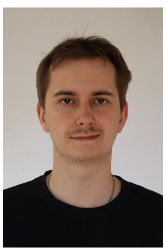

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