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FEASIBILITY STUDY AND OPTIMIZATION OF THE PRODUCTION OF WOOD JOINTS WITH AN INDUSTRIAL ROBOT

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Abstract

Wood is an important and environmentally friendly construction material. Currently, research in the use of wood as a construction material is increasing to improve the sustainability of buildings. The production of wooden components is currently carried out with special and expensive CNC machines (joinery machines) or by hand by skilled workers. A possible alternative solution is the use of industrial robots. However, there is only a limited amount of research and a lack of data in the field of wood machining with serial robots. In order to obtain further application possibilities and data, this paper investigates the feasibility of producing 33 classic wood joints with an industrial robot. For the feasibility study, simulations were carried out, as well as a total of 103 milling tests using a KUKA KR 16-2 with a spindle system. The feasibility study showed that the manufacturing of 29 classic wood joints with an industrial robot is possible and that tolerances of ±1 mm can be obtained. However, there are still numerous optimisation possibilities for the system and the process of wood machining with an industrial robot, which must be further analysed and optimised in future works.

Keywords: Industrial robots; woodworking; milling; wood joints; feasibility study

1. Introduction

Wood is a versatile and environmentally friendly building material and a current research topic in the construction industry to increase the sustainability of buildings [1]. One of these research topics are wood joints. Therefore, the wood industry is currently focusing on traditional and modern wood-wood techniques for joining different wood components and structures [2]. An important factor is the precision in producing wooden components, because a lack of precision in the manufacture of such connections can significantly influence the load-bearing behaviour and lead to damage to the components [3]. The production of the various wooden components in the wood industry is carried out either by expensive CNC machines (e.g. joinery machines) or manually by skilled workers, which can be labour-intensive. Although CNC machines are standard equipment for larger carpentry companies, they are often not affordable for small carpentry companies due to the high acquisition costs, as the corresponding required economic resources are not available or the risks of purchasing them are too high [4]. A possible alternative solution to produce wood joints and other wooden components are industrial robots, as they are associated with lower acquisition costs, allow a more flexible use, offer the opportunity to increase productivity in the woodworking sector and also enable the production of special wooden workpieces [5].

2. Motivation and aim

If the application area of industrial robots for the mechanical processing of wood is compared with other application areas such as aluminium processing, the comparison shows that there is only a small research field with a limited number of research papers in wood processing with industrial robots [4], [6]. In the field of processing aluminium with industrial robots, research papers employ various approaches to increase the accuracy and quality of the manufactured workpieces. For example, Huynh et al. [7] use multibody modelling, simulations and experimental tests to obtain data on cutting forces, vibrations and roughness during milling with an industrial robot. Another approach is to increase the pose-dependent stiffness of industrial robots for the machining tasks [8]. However, the papers in the field of wood processing with industrial robots focus mostly on domain-specific processing and manufacturing of specific components. For example, Geno et al. [9] investigated the processing of unshaped tree trunks and the associated process for automatic robotic manufacturing. For this, they examined the possibilities of connecting tree trunks and the challenges posed by the irregular geometry of tree trunks. In another work, Mesnil et al. [10] designed a robot cell to improve the flexibility in machining and manufacturing of different wooden workpieces for the prefabrication of a 50 m² wooden pavilion. They focused on the workflow and the productivity of the prefabrication. If we now look at the area of timber and the wood industry sector, Pancharowitsch et al. [4], [5], [11] carried out various studies on milling timber with an industrial robot. They conducted numerous experiments, tests and research work with the aim of obtaining objective data for wood processing with industrial robots and thus being able to make comparisons with CNC-controlled joinery machines. According to the authors, there are still large research gaps in the field of wood processing with industrial robots, where there is a lack of usable and comparable information, data, research results, general guidelines and approaches for the implementation and use of industrial robots for wood processing.

To obtain further application possibilities, approaches and data for the processing of wood by industrial robots, the aim of this work is to check the feasibility of producing different wood joints with an industrial robot. Therefore, the achievable accuracy and surface quality of the manufactured workpieces should be determined. Furthermore, a process from the design of the CAD models to the analysis should be created and the milling parameters and milling settings for machining should be determined.

3. Materials and methods

To achieve the goals, a methodology was created based on the approach of Pott and Dietz [12] for the conception and planning of industrial robot systems. In the first step, a potential analysis for the use of industrial robots in the wood industry was carried out and the classic wood joints according to DIN 1052 Section 15 and their subcategories in wood construction were analysed. In the second step, the requirements for the system for wood processing were worked out.

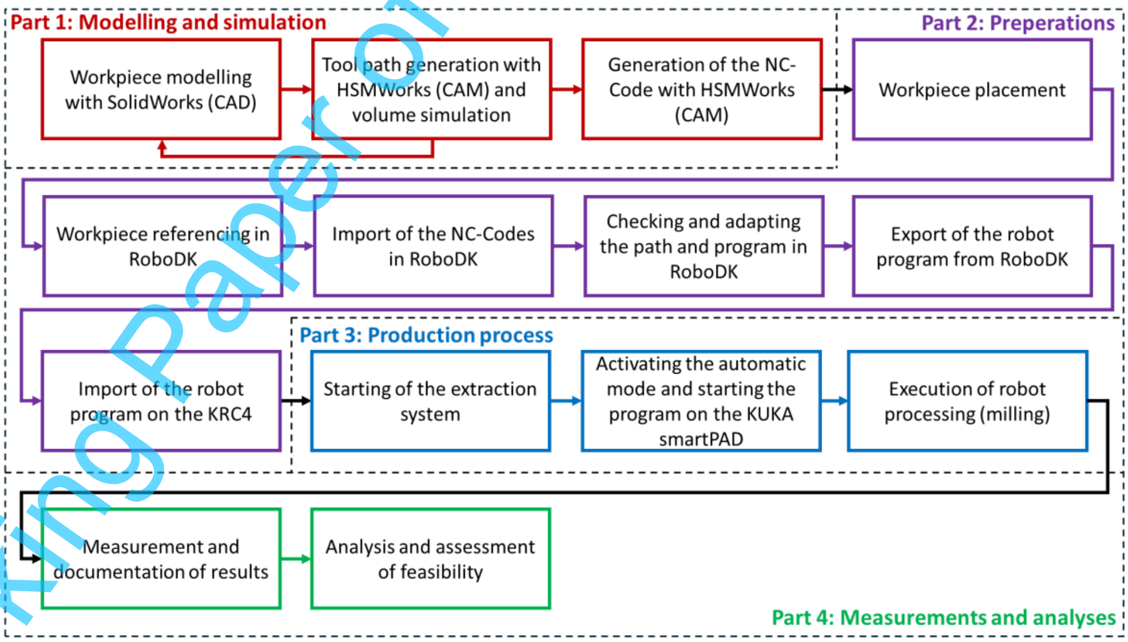

Fig. 1. Overall process from the design to the analysis of the measurement results for the milling tests

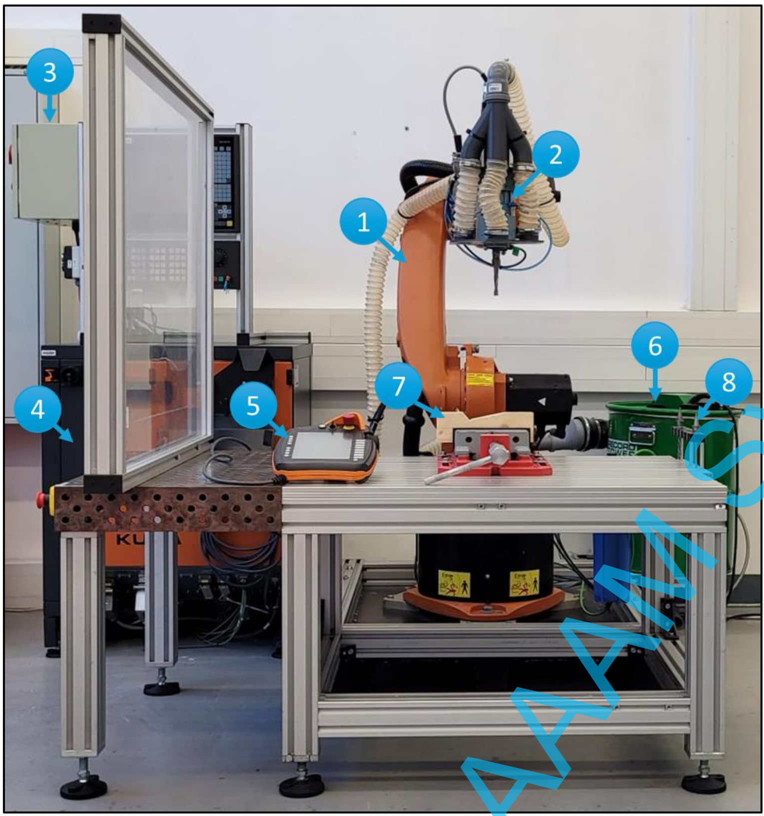

Fig. 2. Robot-Milling-Station of UAS Technikum Wien – 1) KUKA KR 16-2, 2) End effector system with asynchronous spindle, attachment changer and extraction system, 3) Control cabinet with frequency converter, 4) KUKA KR C4, 5) KUKA smartPAD, 6) Extraction system, 7) Clamping system with workpiece, 8) Tool magazine

In the third step, the feasibility study was carried out using simulations and milling tests. Therefore 33 selected wood joints from DIN 1052 were used as workpieces. These wood joints can be divided according to their geometric assignment into the five subcategories: lengthening joints, corner joints, framing joints, oblique framing joints and cross and halving joints. For the feasibility study, only those wood joints that can be modelled in CAD were used. Additional positional securing devices such as bolts, nails, dowels or wedges were not considered in this work. Wooden beams made of spruce or fir with dimensions of 250 mm x 78 mm x 78 mm were used as the workpieces. To carry out the simulation and milling tests, an overall process was created from the design to the analysis of the measurement results of the milling tests. The overall process is shown in Fig. 1.

For the robot simulations and milling tests, the robot milling station at the UAS Technikum Wien was used. This station is equipped with a KUKA KR 16-2, an asynchronous spindle (HFSAC-8022-24-ER16) and an attachment changer from Mechatron. The robot milling station at the UAS Technikum Wien is shown in Fig. 2. Furthermore, various wood milling cutters (with and without chip breaker) with diameters between 8 mm and 12 mm and a dovetail bit for dovetail joints with a diameter of 19 mm were used as milling tools. For the CAD modelling the software SolidWorks was used. As CAM software and for the volume simulations the additional application HSMWorks for SolidWorks was used. Moreover, the simulation and offline programming software RoboDK was used for the robot simulations and robot program generation. With the simulations the possibility of the production of the selected wood joints was checked.

For the milling tests, selected wood joints and their connectors were manufactured with the robot milling station. In addition, for the results of the milling tests a modified version of the criteria for assessing by Pantscharowitsch et al. [4] was used. The modified version includes the two main criteria accuracy (several geometric measurements) and surface quality (optical and haptic assessments for the surfaces and contours). For the accuracy, the mean value of the depth and contour measurements is calculated to compare the results. The measurements were carried out with a digital calliper from Lux with a resolution of 0.01 mm. The surface quality was rated with a value from 4 to 32. Where four is the worst value and 32 is the best value. The feasibility was then assessed based on the simulation and milling results. For this purpose, the tolerance value of ±1 mm was set for the geometric measurements of the milling tests, and the limit value of 16 points was set for the surface quality. The specified tolerance value of ±1 mm lies within all tolerance values of the standards ÖNORM B 1995-1-1:2023 [13] and ÖNORM EN 336:2013 [14]. In the fourth step, an analysis of the problems and the possible optimization options for the system, the overall process and the used hardware and software was carried out.

	Skilled workers	CNC machines	Industrial robots
Strengthen	Very high flexibility	High dimensional accuracy	High flexibility and usability
	Improvisational skills	Standardised and proven machines	Expandable workspace
	Learning skills	High production speeds	High customizability
	Experience	Proven programming	Low acquisition costs
	Adaptability	Efficient production times	Sufficient precision and dimensional accuracy
	Production of new and innovative workpieces		Production of new and innovative workpieces
Weaken	Fatigue behaviour	Limited flexibility	High mechanical compliance
	Low production speed	Limited working space	Complex process
	Limited strength/endurance	High acquisition costs	Missing data and information
	Distractibility	Large space requirement	Low production speed
	Low precision	Limited workpiece placement	Limited number of production system
	Shortage of skilled workers	Limited production	

Table 1. Comparison of the strengths and weaknesses of skilled workers, CNC machines and industrial robots for general woodworking based on the state of the art and the currently possible uses (procedure based on [15])

4. Implementation

4.1. Potential analyses

The potential analysis is based on a comparison of the strengths and weaknesses of skilled workers, CNC machines and industrial robots for general woodworking based on the process of [15] and is shown in Table 1. This comparison shows that skilled workers have a high flexibility and adaptability due to their experience which they can also use for new, complex and demanding processing tasks, such as the manufacture of special wood joints. However, skilled workers have a lower production speed and a lower level of accuracy compared to CNC machines. In addition, CNC machines have a high rigidity and precision which enable high levels of accuracy, repeatability and production speeds.

Although such CNC machines incur very high acquisition costs and require a lot of space. Furthermore, not all wood joints can be produced by standardized CNC machines due to limitations in the kinematics, tools, workspace, processing methods or control system. Compared to CNC machines, industrial robots have lower acquisition costs. Furthermore, they are significantly more flexible, and their workspace can also be expanded. However, there is a lack of experience, data and information in wood processing for industrial robots. This leads to complex processes and currently low production speeds. Nevertheless, industrial robots and their kinematic structure can produce special and innovative workpieces that could otherwise only be manufactured by hand, which is labour-intensive and time-consuming.

Due to the strengths of industrial robots, which are shown in Table 1, industrial robots can be used for numerous tasks in industrial wood processing and manufacturing. They offer potential applications in areas such as handling, testing or measuring, but also in mechanical processing such as milling, grinding, drilling or cutting. These include, for example, the production of wood joints, the production of chipboard panels, the assembly of wooden workpieces, or as part of production lines in wood processing

4.2. Feasibility study

As a first step in the feasibility study, various milling tests were carried out to determine the milling parameters and settings based on the overall process from Fig. 1. These tests were carried out for different milling tools and milling operations, whereby the milling parameters cutting speed, tooth feed and depth feed as well as the position of the workpiece and the robot configuration were varied. For this purpose, wood milling in the form of pockets and grooves was used, with a total of 89 milling tests being carried out and evaluated.

The milling tests for determining the wood milling parameters for the robot milling station showed that for the clearing operations in HSMWorks the "pocket clearing" operation achieved better surface quality with less marks than the "adaptive clearing" operation. Moreover, the cutting speed of 500 m/min and a value of 0.1 mm per tooth for the tooth feed proved sufficient to ensure the highest possible quality for surfaces with this setup. This results in a spindle speed of 15923.57 rpm. For the maximum depth feed, a value of half the cutter diameter is selected to minimize the forces from the milling process and to reduce breakouts and chatter marks. In order to maintain the surface quality, the "feed optimization" function is activated during the milling operation and the "corner deviation" is set to 0.0 mm. Furthermore, the stock-to-leave is selected as 0.5 mm. For the finishing operations of the milling tests, the cutting speed of 600 m/min as well as a tooth feed of 0.08 mm per tooth produced the best results. This results in a spindle speed of 19108.28 rpm. The "feed optimization" is also used for finishing operations and the “corner deviation” is also set to 0.0 mm.

Name of the wood joint	Manufactured connection parts	Manufactured wood joint
Tenon joint		
Oblique thrust joint		

Table 2. Two examples for the manufactured wood joints with pictures of the manufactured connection parts

In addition, the position of the workpiece is chosen close to the robot and centrally in front of the robot according to [16], to improve the stiffness of the system. Furthermore, the CAD models of the selected 33 wood joints were created in SolidWorks. Then the CAM operations were created in HSMWorks. Thus, the determined milling parameters were used for the milling settings of the different operations. With these models and the milling settings from the milling tests above, the volume simulations of the connectors were carried out in HSMWorks. Moreover, adjustments were made to the CAD models to enable processing with the available tools. Then the generated NC-codes from HSMworks were used to create the robot paths in RoboDK. In RoboDK the manufacturable connectors were then simulated again to check the reachability and the production with the industrial robot. After the simulations, seven wood joints were manufactured using the robot milling station. The produced joints were assessed according to the specified criteria. Two of the seven manufactured wood joints can be seen in Table 2.

5. Results

The potential analysis showed that there are numerous possible uses for robots in the wood industry as alternatives or additions to CNC machines and skilled workers. The biggest weaknesses of industrial robots are currently the lack of proven applications in the wood industry and the associated lack of data and information, as well as the complex processes for implementation.

The simulations of the feasibility study showed that the production of 29 of the 33 wood joints is possible by adapting the individual connecting parts to the available tools. Four of the wood joints failed the volume simulation in HSMWorks.

The reason for three of the failed simulation was residual materials in the connectors, which could not be removed by the milling operations. For one wood joint, the total length of the milling cutter was not sufficient, and the tool holder collided with the workpiece.

Fig. 3. Occurred chatter marks caused by vibrations and oscillations of the system

Furthermore, the results of the simulation tests in RoboDK showed that all wood joints that passed the volume simulation with HSMWorks also passed the simulation tests in RoboDK. In order to be able to manufacture the four connections that could not be produced, further tests with additional tools and further adaptations to the connections are necessary.

The milling tests of the connectors showed that in 13 of 14 milling tests, accuracies between -0.020 mm and 0.378 mm were achieved. One milling test achieved an average deviation of 1.325 mm due to a work object measurement error, which was outside the specified tolerance of ±1 mm. However, the tolerance could be maintained for the identically constructed connecting piece without any work object measurement errors. All surface qualities of the milling tests were above the specified limit of 16 points. Surface quality ratings between 20 and 28 out of a total of 32 possible points were achieved. The reasons for the low ratings were chatter marks on the surfaces, which can be seen in Fig. 3. These machining marks were caused by vibrations and oscillations of the system. To further reduce the chatter marks, further optimizations and tests must be carried out.

The simulation and milling tests showed that there are still challenges and optimization options for the manufacturing of wooden components with a KUKA KR 16-2 and the selected process to improve the quality of the production. In addition to the already mentioned chatter marks, the multi-sided machining of the workpiece is a challenge. At the moment, the component has to be moved by hand and referenced again each time. This is time-consuming and also leads to inaccuracies due to referencing errors that add up. A possible optimization options here is an additional clamping system that can rotate the workpiece to enable multi-sided machining of the workpiece in one operation. Another inaccuracy factor is the referencing and calibration of work objects and tools. The referencing of the work object is currently carried out by hand using the 3-point method from RoboDK via XYZ points, which can lead to inaccuracies during machining. Moreover, the TCP calibration functions from RoboDK is labour-intensive and error-prone for milling tools, which leads to additional work for the tool measurement process and to inaccuracies for the TCPs.

6. Conclusion

To sum up, it can be said that woodworking offers great potential for the use of industrial robots with numerous possible uses in the wood industry, such as the production of wood joints. However, there is a lack of information, experience and data for the use of industrial robots in the manufacturing of wood, which need to be further researched to enable the correct use. For this a feasibility study was carried out, to generate data und to verify the production of wood joints with an industrial robot.

The feasibility study, with various simulations and milling tests showed that the production of wood joints is possible using an industrial robot for milling. However, there are limitations regarding to the used hardware and software. For example, with the used milling tools and the CAM software HSMWorks four of the 33 wood joints could not be manufactured. To be able to manufacture these joints with an industrial robot for milling, further tests with additional tools are necessary. Furthermore, other CAM software should also be considered to check the manufacturing of the wood joints and to obtain additional results. Moreover, the milling tests showed that accuracies within the tolerance range of ±1 mm can be achieved if precise work object measurement is ensured. The results also show that the achieved accuracies are sufficient for processing of wood joints and construction timber. The evaluations of the surface quality ranged between 20 and 28 out of a total of 32 points, which is sufficient for the production of wood joints. The reasons for the low ratings are chatter marks on the surfaces. These chatter marks are visually recognizable, but do not affect the function of the joints. Thus, while the surface qualities are sufficient, it still offers potential for further optimization.

There are also other optimization possibilities for such a woodworking system with industrial robots, which must be analysed and addressed in further works. This includes for example, optimizing the overall process, which has numerous different interfaces. These interfaces generate additional effort during the process implementation. An example for this is the additional creation of the robot programs in RoboDK for the KR C4 and the following transfer from RoboDK to the KR C4 for each milling process. Other optimization options are the improving of the stability of the system to reduce the chatter marks and optimizing the complex and error-prone measurements for tools and work objects, which are needed to ensure a flawless production of the joints and other wooden components.

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