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Automating 3D printing for mass production

(b) Felix Daunert[1], Prof. Dr. Tobias Weiser[2], Prof. Dr. Dirk Jacob, Maximilian Besler, Florian Schmolke*

***Abstract*— This paper presents the development and evaluation of an automation concept for high-performance 3D printers in an industrial environment. The paper's special characteristic is the multi-domain approach, which combines design and development of the cell with parallel simulation studies. The 3D printing robot cell was complimented with an individual gripping system and a magazine for printing plates. The final production performance of the concept was evaluated with simulation studies of the robot cycle time and overall performance.**

***Index Terms*— Automation, 3D printing, Simulation**

I. INTRODUCTION

This paper presents the development of an integrated automation concept for an industrial 3D printing farm with a production capacity in excess of one million parts per annum. The focus was on the integration of automated loading and unloading of a Masked Stereolithography (MSLA) high-speed 3D printer (Solidator 8K [6]) by a 6-axis robot (KUKA KR10 R1100). This project integrated offline simulations and time-valued Petri nets in the design of the automation concept to enhance the overall performance of the concept. The analysis is conducted using KUKA.Sim and Siemens Plant Simulation, where cycle times, material flows and path planing is layed out and optimised. The final concept demonstrates high production capacity and scalability, making it a promising alternative to existing industrial solutions.

II. STATE OF THE ART

Additive manufacturing (AM) is currently experiencing an increased integration of automated processes with the objective of enhancing production efficiency and improving profitability like the Figure 4 Production by 3D Systems [3]. This system provides a comprehensive solution that integrates printing, cleaning and UV curing in a single module. However, this solution is costly and exhibits limited flexibility with regard to scalability. Other manufacturers offer retrofit options that allow partial automation, such as part removal (see Form Auto, Formlabs [4]). However, AM technology requires good automation and scalability for series production [1]. Modular automation concepts, in contrast, are distinguished by a deliberate selection of printing technologies, optimised cell layouts and process optimisation based on simulation. To ensure increased automation and scalability, it is necessary to employ simulation software such as KUKA.Sim and Plant Simulation. This approach facilitates the determination of realistic operating parameters and consequently enables the evaluation of the developed concept against the requirements.

III. REQUIREMENTS ANALYSIS

In order to achieve an annual production of at least one million parts with dimensions of 50 mm x 30 mm x 20 mm (W x D x H), a calculation of the required number of printers and print cycles is necessary. In this context, the Solidator 8K was identified as a suitable solution, given that its printing time is solely dependent on the part height and it possesses a substantial build plate with dimensions of 330 mm x 185 mm. For automation purposes, an actuator is requisite. This actuator must meet certain requirements, namely the capacity to securely grip the printing plates, a minimum load capacity of 2.5 kg, and six degrees of freedom to facilitate the dexterous manipulation of the printing plates. Furthermore the workspace must accommodate six printers.

IV. GRIPPER AND MAGAZINE DESIGN

In the course of the conception a two-finger gripper was developed for the handling of the printing plates by the robot. Its an asymmetrical construction with the objective of avoiding collisions with the printing bed. The gripper construction, see Fig. 1, was designed with consideration for mechanical and dynamic aspects in order to ensure the secure grasping of the printing plates.

Fig. 1. gripper (with print bed on the left)

A modular magazine functions as a print plate buffer between the outsourced reprocessing and the loading of the print plates. The magazine and the gripper are both crucial for a comprehensive simulation of the system's processing time and, by extension, its productivity. The magazine is employed as a station for the taking of new plates, while the gripper enshures the precise path planing during grasping and handling of these plates.

V. ROBOT SELECTION

A 6-axis kinematic system is evidently the optimal solution, as the requirements clearly indicate. The 6 Solidators

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[1] Felix Daunert, Student of Automation and Robotics, Faculty Electrical Engineering, University of applied science Kempten, 87435 Kempten, Germany felix.daunert@stud.hs-kempten.de

[2]Prof. Dr. Tobias Weiser is with Institute for Applied AI and Robotics, University of applied science Kempten, 87435 Kempten, Germany tobias.weiser@hs-kempten.de

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are arranged in a U-shape around the kinematics. A reach analysis in KUKA.Sim revealed that the KUKA KR10 R1100 meets all requirements with a reach of 1100 mm, a payload capacity of 10 kg and a repeatability of ±0.02 mm. These parameters ensure that the printers can be processed with the requisite precision and without collisions in a centrally arranged cell.

VI. Robot simulation

The movement patterns of the integrated robot system were modelled and simulated in KUKA.Sim, with CAD models of the U-arrangement of the Solidators around the kinematics, the print plate magazine and the gripper being imported (see Fig. 2). These must be integrated into the simulation to ensure precise programming of collision free movement patterns of the kinematics. A black box is utilised as a depository for the printed plates, since there was no interface to subsequent stations defined.

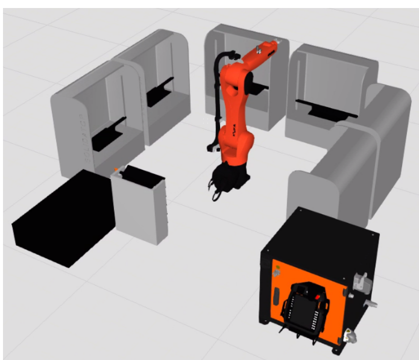

Fig. 2. KUKA.Sim Layout with black box and magazine on the left

The outcomes of the simulations demonstrate that the KR10 R1100 is capable of achieving an average cycle time of 15.5 seconds per printer. These results take into account critical movement segments, such as the reduction in acceleration during the transportation of printed plates. The reorientation required for each printer has small effect as the maximum deviation of the mean is 1 second. This is due to the tool center point (TCP) speed of 2 $\frac{m}{s}$ while reorienting. The majority of the mean cycle time is spent picking up and setting down the printing plates at a reduced TCP speed of 0.1 $\frac{m}{s}$. Utalizing these simulations enabled the programming of collision-free motion sequences and the determination of real cycle times for the robot. This data is imperative for simulating the overall task.

VII. Total cycle simulation

The basis for the overall process simulation in Plant Simulation is a time-evaluated Petrinetwork, in which a shift calendar has been introduced for the simulation of a calendar year. This is due to the fact that maintenance, potential repairs and the replacement of the resin reservoirs are manual tasks. The calendar is modeled on a working week from Monday to Friday 8 hours daily, and takes into account conditions such as availability. The educated guess is made that the printers are available at 95% of the time and the kinematics at 100%, which is regarded as ideal. The duration of the printing process is either 20 minutes for 80 standing parts or 6 minutes for 24 lying parts with a constant setup time of 2 minutes and a processing time of 15.5 seconds by the kinematics. The simulation examined the standing and lying arrangements of parts on the plates, with the upright configuration resulting in a higher part production due to a reduced proportion of setup time in the total operating hours. For the calendar year, a standing arrangement of parts on the plate yielded a theoretical annual output of 2.3 million parts. This calculation is based on the utilisation of 6 Solidator 8Ks and a KUKA KR10 R1100 kinematic system. The scalability of the system is evident in its ability to accommodate the placement of the kinematic structure on a 300 mm-high platform, enabling the construction and processing of an additional second storey comprising 6 solidators. Furthermore, the robot demonstrates the capacity to efficiently handle twelve solidators, resulting in an average cycle time of 16.5 seconds.

VIII. Conclusion

In this project, an automation concept was developed that uses 6 Solidator 8K printer in combination with a precisely matched 6-axis robot (KUKA KR10 R1100) to realise an efficient and scalable 3D printing farm. The optimisation of production was achieved through the targeted use of offline simulation and time-weighted petri nets, resulting in an average kinematic processing time of 15.5 seconds per printer. The developed solution has been shown to exceed the production target by a factor of 2.3, thus representing a commercially viable alternative to existing industrial systems. The scientific significance is high for the robot cycle time but reduced by the educated guesses concerning the availability and setup time of the printers.
Future research should focus on implementing real printer characteristics for further optimizing. There is the potential trough artificial intelligence in the domain of path planning [5] or in Petrinetworks [2] to enhance flexibility and efficiency of the cell.

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