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Design and implementation of a digital infrastructure for autonomous open-die forging

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Abstract

Open-die forging is a key process for manufacturing large components such as generator shafts and crankshafts for ship engines. Despite its industrial relevance, the process remains dependent on manual labour and operator expertise, leading to challenges in process stability, reproducibility, and efficiency. Traditional automation approaches are impractical due to the high variability and low production volumes typical of open-die forging. At the Institute of Metal Forming (IMF) at the TU Bergakademie Freiberg, a novel concept for autonomous open-die forging has been developed and tested. The system combines conventional forging equipment with advanced technologies, including industrial robotics, 3D laser scanning, thermal imaging, and modular control software. Central to the concept is a robot cell operating as a distributed system, where sensor data is used to create a digital twin of the workpiece. This enables adaptive process planning and real-time autonomous operative adjustments. A process planning tool generates pass sequences and commands for manipulator movements, while an electromechanical interface allows indirect control of the forging press. The modular software architecture, coordinated by a central core-module, ensures flexibility and facilitates integration into different production environments. Initial trials demonstrate the system's potential to improve process stability and quality while reducing dependency on manual operation. Ongoing work focuses on refining the concept to meet industrial requirements and support advanced material applications.

Keywords: automation, forging, open-die forging

1. Introduction

Open-die forging, as an incremental metal forming process for highly individual parts, remains heavily dependent on manual work. The handling of large components weighing up to hundreds of tons, the low production volumes, and the high variability in materials, geometries, and production volumes present major challenges for maintaining stable process conditions. When it comes to advanced materials like superalloys, titanium, or nickel-based alloys, the metallurgical integrity and quality requirements rise significantly (Rao, 2021).

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It is common practice to use FEM methods to simulate the entire open-die forging process and make precise predictions of material behaviour. However, the production environment involves numerous variable process parameters, such as temperature, transport times, operator experience, and the actual execution of the designed pass sequence. These variations often introduce discrepancies between the planned and actual process, resulting in inconsistent part quality. Various approaches have been developed to adapt the pass sequence in real-time to address variations in the open-die forging process (Dindorf et al., 2021; Riedel et al., 2019).

Using different measurement techniques to detect process parameters, geometry, and temperature of the workpiece, each approach uses specific inputs to calculate the optimized pass sequence for its own use case. However, most of these approaches can only assist the operator with suggestions because there is no direct connection to the forging equipment, such as the manipulator and the press. This concept improves the forging process but still has the same vulnerability for variations (Hirt et al., 2016).

Conventional automation approaches relying on fixed sequencing and pre-programmed manipulator movements are insufficient to address the demands of open-die forging. A key challenge is the lack of flexible interfaces that can connect dynamic pass sequence calculations with real-time measurement data and process control systems. Despite numerous attempts to automate open-die forging over the past decades, a fully automated and robust system with the flexibility to change the pass schedule optimization algorithm has yet to be realized.

To address this challenge, researchers at the Institute of Metal Forming at the TU Bergakademie Freiberg have developed a novel concept for autonomous open-die forging. The design incorporates 3D geometry measurement, temperature monitoring, a KUKA robot as a manipulator and a forging press, and adaptive process planning with a flexible automation interface to create a comprehensive digital infrastructure for autonomous open-die forging. The design concept and implementation of this innovative system is presented.

2. Brief historical summary of open-die forging automation

The first attempts at using automation in open-die forging focused on simple geometries like round or square bars with a constant cross-section were presented in the late 1970s by Heginbotham and Appleton (Heginbotham et al., 1979). The main goal was to use a 5-axis robot as a programmable manipulator. The robot was able to execute fixed programs while a confirming signal from the operator by pushing a button was necessary. The small press was controlled by an electro-hydraulic circuit. The pass sequence was calculated offline based on user input and some simple material flow models like the Tomlinson Stringer approach (Tomlinson & Stringer, 1959). This early approach contributed to demonstrating the general feasibility of adapting automation to open-die forging for repeating geometries based on a computer. As a result, the authors suggested a more general open-die forging system consisting of furnaces, forging press and measurement stations.

Over subsequent decades, researchers built upon these initial automation efforts, developing more advanced process planning algorithms and integration strategies to enhance the flexibility and adaptability of open-die forging automation systems. The ongoing advancements in information technology and increasing computational capabilities facilitated this progress. In the early 1990s, Lilly & Melligeri (1996) worked on an intelligent forging system intended to utilize many features proposed by Heginbotham and Appleton (Heginbotham et al., 1979), such as a control system for operating the robot, furnace, and press. They employed modern calculation methods which were quite ahead of their time like finite element analysis and neural networks to address the challenges.

To enable the online calculation of material flow for the pass sequence calculation, fast material flow models are crucial. Researchers have explored various approaches to address this issue, particularly for simple-shaped geometries like squared bars. The work of Aksakal et al. (1997) has demonstrated progress in this area. Additionally, Nye et al. (2001) conducted research on the real-time process characterization of material flow, focusing on the spreading behaviour of squared bars based on process data in the late 1990s, and implemented their findings within a forging cell. The integration of these advancements into a production setup remained an interest, especially in terms of the interaction between the manipulator and the press, as explored by Osman & Ferreira (1999). Elbadan's research in the early 2000s focused on the adaptive scheduling of open-die forging processes. By leveraging online measurement data of shape errors for squared bars and wedges, his work explored methods to optimize the pass sequence and improve the overall quality and consistency of the forged parts (Elbadan, 2004).

In 2009, a research team led by Wang developed a robot-controlled open-die forging cell to manufacture semi-finished titanium parts for artificial bone appli-

cations. They conducted basic investigations to create bent geometries using open-die forging with a 6-axis robot as the manipulator (Wang et al., 2009). However, this project did not integrate automated pass sequence optimization due to the specialized nature of the use cases. This overview reveals a trajectory of continuous improvement in automation strategies for open-die forging, with each successive contribution building upon previous efforts to expand the capabilities and applicability of these systems.

My et al. (2018) introduced a novel, lab-scale robot arm designed for hot forging press automation, focusing on the automated handling of hot workpieces to improve productivity and safety. The robot incorporates parallel links between serial links and hydraulic actuators to achieve high structural rigidity, addressing the challenges of handling heavy payloads at high speeds. The design aims to simplify workpiece handling, improve positioning accuracy, and ensure stability during rapid movements of hot materials within a forging press setting.

In 2019, Wolfgarten (2019) introduced an innovative method for forging curved components using open-die forging. The process involved an oil-hydraulic robot from GLAMA Maschinenbau GmbH in combination with a 6.3 MN forging press from the SMS group, enabling the superimposition of manipulator movements during forging. By incrementally repeating this approach with an adapted pass sequence, curved billets with radii ranging from 257 mm to 1,100 mm were successfully produced. Notably, a curvature of 270° was achieved with the smallest radius of 257 mm, demonstrating the significant potential of using high-degree-of-freedom manipulators or robots in forging processes.

Behery et al. (2020) address the challenge of automating open-die forging, a metal-forming process heavily reliant on human experience due to the lack of real-time quality measures. In this process, a robot arm manipulates a workpiece between the dies of a forge, which strikes the workpiece repeatedly to achieve the desired geometry. Behery et al. introduce a computer vision technique to discretize the robot arm's teleoperated actions into distinct actions, which the authors present as a step toward understanding and learning the operator's behaviour and eventually achieving shared autonomy. The work aims to improve the consistency and quality of the forging process by capturing and replicating the operator's expertise.

In addition to the use of robots in open-die forging, recent years have seen a growing focus on developing advanced strategies for pass sequence design. A key trend in this area is the implementation of online approaches that rely on fast empirical or semi-empirical models, which offer significantly lower computation times compared to finite element methods. For example, Rudolph et al. (2021) propose an assistance system that utilizes such fast models to support the forging process. Although their optimization model is not yet suitable for real time applications, it still provides valuable insights. The system aims to maintain a defined temperature window and introduce sufficient deformation to refine the microstructure, transforming the initial cast structure into a fine-grained one to achieve the desired mechanical properties. The authors demonstrate that, while the model cannot yet react in real time, it can still be used to predefine or adjust pass sequences in response to expected process deviations.

Reinisch et al. (2021) presented a method for autonomous pass schedule design in open-die forging by coupling fast process models with a double deep Q-learning (DDQL) algorithm. The fast models enable quick prediction of workpiece and process properties, allowing their direct integration into the schedule design. The approach was tested offline and proved robust across different conditions, generating optimized schedules within 2–4 s – demonstrating its potential for future online application.

Despite numerous attempts to automate open-die forging, develop intelligent pass sequence design, and implement measurement technologies for conventional forging plants with a common manipulator and press, these solutions often targeted specialized use cases and had closed infrastructures, making it challenging to scale them to general solutions for other forging plants. Additionally, the pass sequence planning was only applicable to limited geometries and materials. The solutions also lacked a comprehensive approach, with measurement, process planning, and monitoring often implemented as separate systems without a unified infrastructure. To address these challenges, a novel concept for an open infrastructure for autonomous open-die forging with a robot cell was developed, which combines 3D geometry measurement, temperature monitoring, adaptive process planning, and flexible automation interfaces to create a modular digital infrastructure for autonomous open-die forging.

3. Experimental setup

The forging cell is equipped with a KUKA KR360 L280-2 industrial robot (1), which serves as the manipulator for handling and positioning the workpieces. A 10 MN oil-hydraulic press from Wepuko Pahnke (2) carries out the forging process, and a furnace (3) is used for heating the workpieces before forging. To

ensure precise process monitoring, a custom-designed 3D scanning system (4) captures geometric data, enabling the creation of a digital twin of each workpiece. Additionally, thermal imaging cameras provide continuous temperature monitoring, supporting process optimization and control. This comprehensive setup ensures that the forging process is closely monitored and controlled, allowing for precise adjustment and optimization of the manufacturing parameters to achieve high-quality, consistent forged parts. The forging cell equipment is shown in Figure 1.

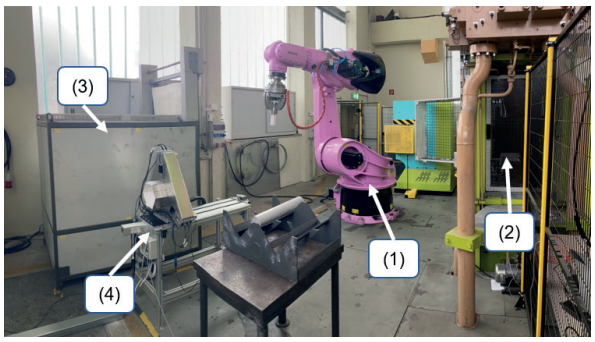

Fig. 1. Forging cell equipment

3.1. Scanning system

The scanning system used for capturing the workpiece geometry and temperature is a custom development. It is equipped with three blue-light line lasers of the type "scanCONTROL 2900-100/BL" from the manufacturer Micro-Epsilon, mounted in a plane at an angle of 120° to each other. This configuration allows for the complete cross-sectional measurement of a workpiece.

Three thermal imaging cameras of the "PI 1M" type from Optris are installed at the same orientations to capture the local temperatures of the workpiece surface. Both the line laser sensors and the thermal imaging cameras are shielded from high temperatures by metal plates coated with an insulation layer. Cutouts have been introduced exclusively at the measurement positions, and the plates have been blackened to minimize potential measurement errors due to reflections.

The entire unit shown in Figure 2 is mounted on a linearly movable table that can be displaced using a spindle, with a total travel range of 700 mm. During the scanning process, the robot positions the workpiece in the centre of the measurement frame, and the scanning system then moves along the longitudinal axis of the workpiece while constantly making cross-sectional scans and recording temperature profiles. Connected to the current position of the measurement frame, a 3D dataset is generated, which serves as the basis for calculating the pass sequence, requiring the determination of the individual scan positions and their associated data. After the process, the scanning system returns to its initial position. The movement is controlled over the PLC of the KUKA control system to ensure that there is similar movement of both components.

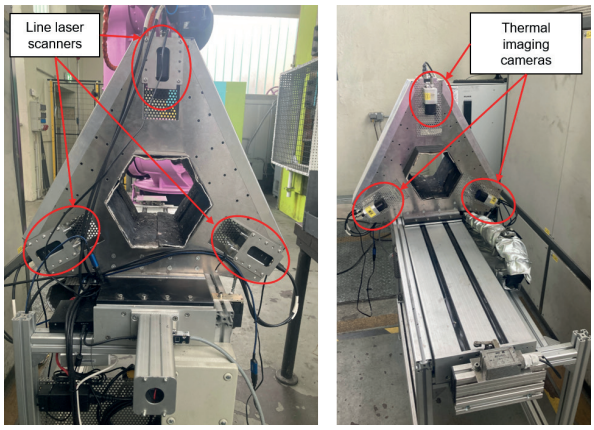

Fig. 2. Scanning system

The manufacturers of laser scanners and thermal imaging cameras provide software developer kits as DLL files, enabling connection to the sensors and data retrieval. The laser scanners are connected via Ethernet, while the thermal imaging cameras are connected via USB to the main PC. During implementation, a handler manages the laser scanners to address issues with overlapping laser lines, which can lead to interference in the measurement data. The scanning system's general management is handled by its own abstracted module. This approach allows for individual or combined control of each sensor, providing good exchangeability and extendibility of the system. To make the measurement data accessible for other applications, the raw data is stored on the main PC, serving both pass sequence planning and future use cases.

3.2. Robot integration

The integration of the robot into the communication infrastructure centre around the RoboDK software, which enables communication with the robot via an Ethernet connection and provides access to a comprehensive, well-documented programming interface. Initially, the entire robotic cell, including all relevant components, was virtually modelled. The key components include the robotic arm (1), a universal oil-hydraulic forming press (2), a furnace (3), and a scanning system (4), as shown in Figure 3.

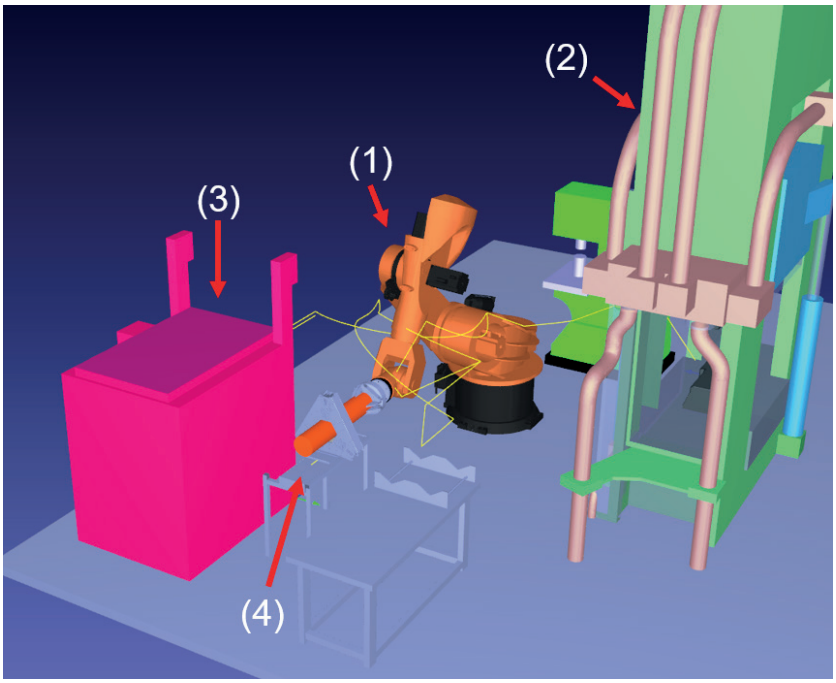

Fig. 3. Digital twin of the robot cell, including the dummy workpiece and the planned transport paths between the individual components

The robot movements are executed by calling sub-routines, in which the transfer path between two cell devices is described (yellow thin line in Figure 3). Those paths were calculated based on an oversized dummy workpiece (the orange coloured cylinder in Figure 3) to avoid collisions. The movement velocity was also configured within RoboDK software and successfully tested in the real robotic cell. Additionally, subroutines were developed for controlling the pneumatic gripper and the furnace door via digital inputs and outputs of the PLC in the control system of the KUKA robot. The gripper operates by briefly activating a digital output to open or close the valve. After the specified duration, the output is deactivated. The furnace operates in a similar manner, but it uses limit switches to indicate its open and closed positions. Beyond the predefined programs for the furnace, gripper, and transport paths, a method was implemented to control the robot's movements based on measurement data, particularly for commands from the process planning system. Two critical process steps involve placing and removing the workpiece from the furnace, as well as positioning and interacting with the press during the forging process. For this purpose, a function for linear relative movements was implemented within the core module. Starting from an initial position, which serves as a reference coordinate system after transport to the furnace or press, the workpiece can be precisely positioned based on measurement data. In the current process planning system, correction movements for tilting the workpiece in two dimensions are calculated. The workpiece is then rotated according to the pass sequence or edge detection and placed in the furnace or on the forging die, taking into account the component thickness or diameter.

During the forging process, the bite length is also adjusted. Since the robot currently lacks the ability to independently compensate for material flow during forging, the workpiece is first placed on the lower saddle. Afterwards, the press closes to precisely clamp the workpiece. The gripper then releases the workpiece, and the process goes on according to the stitching plan data. The robot adjusts the position of the gripper based on the predicted material flow in height and length, as determined by process planning calculations, before gripping the workpiece again. The press then opens slightly, and the workpiece is moved to the next position as per the pass sequence until the entire plan is executed. After the final stroke, the robot returns to its initial position and moves to the scanning system using predefined transport programs.

However, this forging process is time-consuming and not optimal in terms of economic and process efficiency. To address these limitations, future work will focus on upgrading the robot to either operate with force control or utilize a gripper capable of compensating for material flow, improving the overall efficiency of the forging process.

During operation, RoboDK must remain open, a connection to the robot controller must be established,

and the corresponding KRL script must be started on the robot control system. Once these conditions are met, all RoboDK programs and functions can be sent as instructions for the robot to execute.

3.3. Press integration

The integration of the press into the forging process requires an electro-mechanical interface to regulate its movement. Since the existing press control system was not designed for external control and no dedicated interface was provided, an alternative approach is necessary to enable automation.

Instead of modifying the internal control electronics, the system replicates manual operations by automating a press lever with a tilt angel-press velocity controlling system. A servo motor is mechanically coupled to the lever, translating digital commands into lateral movements while ensuring compatibility with existing safety mechanisms.

To enable precise positioning, an external displacement sensor continuously monitors the press position. Communication is established via Ethernet/IP, with a microcontroller acting as a server to process movement commands and transmit real-time position data.

Given the limitations of this workaround, no further improvements will be made to the current system. Instead, a full modernization of the press electronics and software is planned, incorporating an open interface for seamless integration into future automation solutions. This upgrade will significantly enhance the control and responsiveness of the press, paving the way for more advanced and efficient forging processes.

3.4. Digital Infrastructure

The use of a core module as the central integration point for the robotic cell's major software components has significantly enhanced the system's flexibility and maintainability. By reducing dependencies between individual modules, the core module allows each component to be modified, upgraded, or replaced independently. Standardizing communication and data exchange enables seamless interaction between the scanning system, process and stroke planning tool, and the digital twin in RoboDK. The core module, process planning module, and sensor interactions were implemented in Python, leveraging the existing APIs and software development kits provided by the manufacturers. The script running on the KUKA Robot Control 2 (KRC2) system was written in the robot-specific KUKA Robot Language (KRL). The position measurement system of the scan system and the press interface were implemented using microcontrollers with software written in C.

This modular approach has streamlined the implementation of changes. Instead of adapting multiple components, only the core module requires adjustments allowing extensions to new functionality or alternative subsystems. For instance, introducing a different scanning system or an alternative process planning algorithm would result in minimal changes to the core module, preserving the overall system architecture (Fig. 4).

This scalable and adaptable architecture not only simplifies future modifications but also establishes the foundation for a robust autonomous robotic forging system.

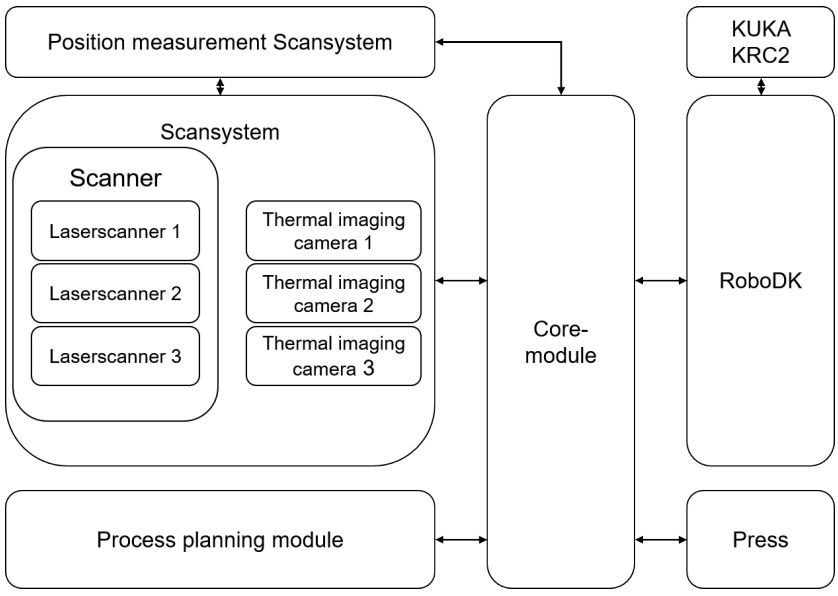

Fig. 4. Digital infrastructure of the forging cell

4. Experimental validation

As part of the NanoBainControl project (M-Era.Net), the setting up of the forging process was integrated into the software architecture. The process and stroke planning tool were developed alongside the architecture and adapted accordingly.

The process begins with the robot retrieving the workpiece from a predefined position and transporting it to the scanning system for geometric measurement, as illustrated in Figure 5a (in this case, with a preheated workpiece). In the currently used process planning module, the geometry data is converted into a geometry model based on a polar coordinate system, as shown in Figure 5c. This model is derived from raw measurement data acquired by the blue light line laser scanners, each providing up to 1,280 data points. Before the model can be generated, the raw data must be preprocessed to eliminate points that are not associated with the workpiece cross-section. Additionally, the transformation algorithm must account for faulty or missing data, which can result from challenging environmental conditions – such as smoke affecting the optical system – or from the workpiece being only partially within scanners measurement field. If the workpiece temperature is within the measurement range of the thermal imaging cameras (450–1,800°C), the temperature data (Fig. 5b) is mapped onto the geometry data to generate a digital twin of the workpiece, as shown in Figure 5d. This is achieved by correlating the temperature profile from each thermal imaging camera with the corresponding geometry data captured by the laser scanner at the same position. The offset between the laser scanner and the thermal images is taken into account to ensure that each temperature profile extracted from the thermal image is accurately aligned with the correct geometry data. Any missing data is approximated through interpolation.

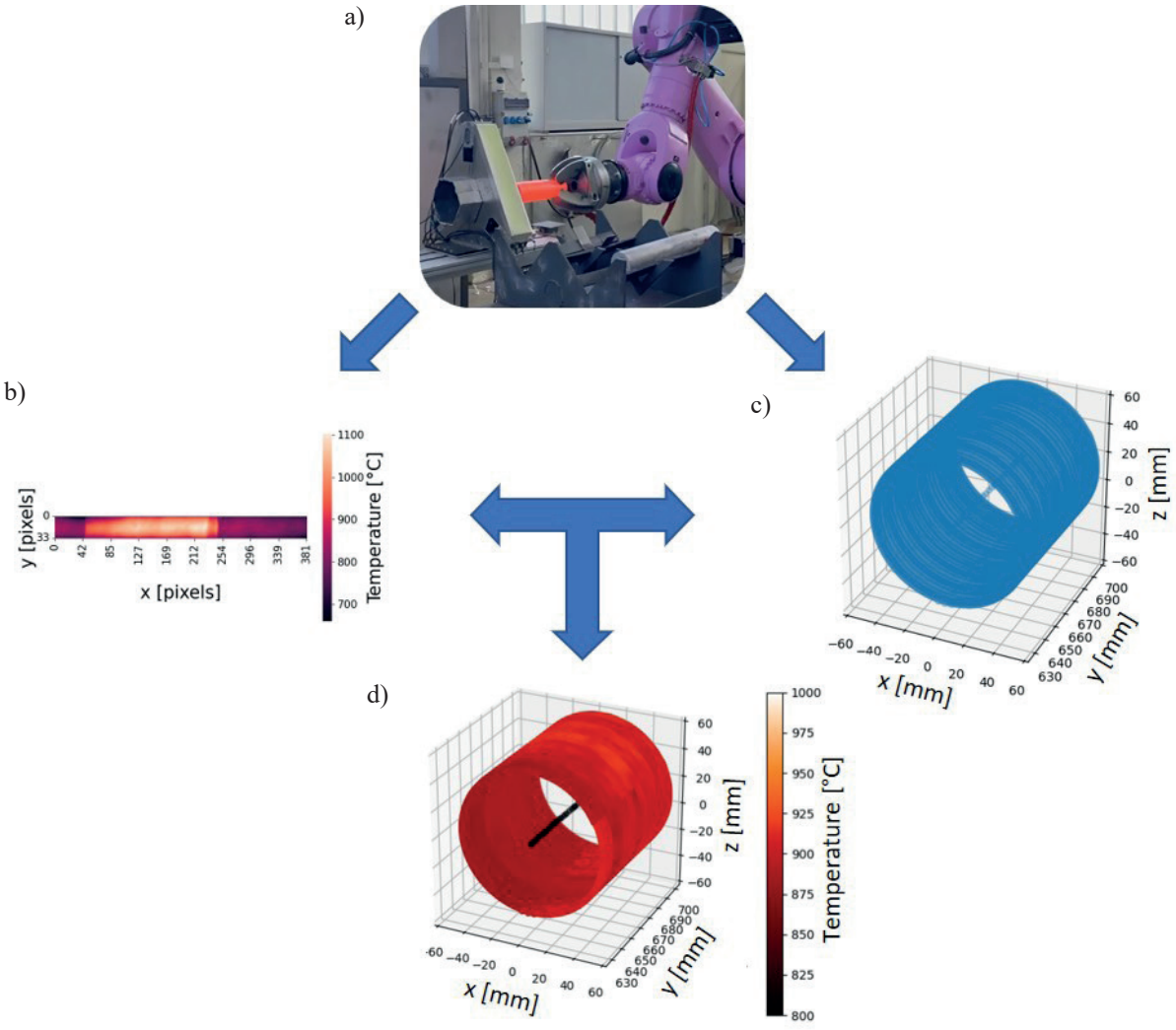

Fig. 5. Acquisition and processing of measurement data: a) scanning process; b) thermal image of one camera; c) processed geometry model based of the laser scanners data; d) digital twin of the workpiece based on correlation of geometry and temperature data

Next, the workpiece is positioned in the furnace. A routine implemented in the core module analyses the 3D geometry to determine necessary tilt adjustments and optimizes the placement orientation. To determine the alignment of the workpiece, the tilting of the centre points of each cross section (marked in black in Figure 5d within the digital twin of geometry and temperature) is evaluated. Based on this, the tilting angles around the x- and z-axes are calculated to generate the necessary rotational compensation. Additionally, the translational offsets in the x- and z-directions are determined by measuring the distance between the centre point of the cross-section closest to the robot gripper and the origin of the coordinate system.

Once the alignment is complete, the process planning tool analyses the workpiece geometry for edges. If an edge is detected, the system will prefer an orientation by rotating the workpiece around the y-axis to ensure proper positioning. If no edge is found, as in the case of cylindrical workpieces, the current rotation angle is maintained.

In total, the system calculates two tilting angles (x and z), two translational offsets (x and z), and the rotation angle around the y-axis. Additionally, the workpiece thickness at the current position is computed to inform the robot how much it must lower the workpiece during placement. The robot then precisely deposits the workpiece into the open furnace. After exiting, the furnace is closed, and the workpiece is heated for a predefined duration.

After heating, the robot grabs the workpiece and moves it to the scanning position to verify the exact gripping orientation, the geometry and to measure the surface temperature, like it is shown in Figure 5. The updated data is fed into the process planning tool, which calculates the forging sequence while the robot moves the workpiece to the initial forging position.

The tool receives a predefined number of passes, the bite width, and specific geometrical parameters as inputs. Once a pass, consisting of multiple strokes along the full longitudinal axis of the workpiece, is computed, the robot executes the corresponding forging pass while the next passes are calculated in parallel. The pass sequence calculation is based on a comparison between the target geometry and the scanned geometry using cross-sectional data in Figure 6. Both geometries are provided in polar coordinates to the planning tool. The centre axis of the polar coordinate system is aligned with the longitudinal axis of both geometries, which corresponds to the y-axis of the Cartesian coordinate system shown in Figures 6a and c. The 0° angle is aligned with the positive x-axis, and 90° is aligned with the positive z-axis. To enable a direct comparison of the data point vector lengths, both geometries must be defined at the same y-position and angular orientation. The comparison is performed using a set of cross-sections along the y-axis to obtain a representative distribution of local geometric deviations, like it is shown in Figures 6b and d (Rechenberg et al., 2023). Based on the geometric deviation between the scanned and the target geometry, the algorithm calculates an angle for the forging operation, using weights to prioritize deviations at the edges of the target geometry.

Deformation is calculated using a pillar model which applies the Tomlinson–Stringer approach to estimate spreading. However, the material-specific spreading behaviour has not been validated yet. The calculation is performed section by section. To improve accuracy, particularly with regard to die radius, multiple cross-sections are interpolated and incorporated into the spreading calculations, as shown in Figure 6c. The elongation of the workpiece is determined using the assumption of constant volume. The deformation is calculated for every press stroke of a pass individually.

The forging process continues until the target geometry is reached or the maximum number of passes is executed. After forging, the workpiece is scanned again to verify the final shape. This process can be repeated as needed until the target geometry is achieved or the maximum iterations are reached. The calculation time in this method depends on several factors, such as bite length, number of press strokes per pass, density of cross sections to be compared, and the density of cross sections interpolated for calculating the shape at the die radius. For the example shown in Figure 6, the average calculation time on a workstation PC with an Intel Core i9-10900K processor was approximately 1.6 s for calculating the material flow for one press stroke. This is the most time-consuming step, which is often called multiple times. The second most crucial function, the comparison of the geometries, takes 0.93 s per call on the same setup. Finally, the robot places the finished workpiece on the table and returns to its starting position, completing the cycle. A scheme of the process is shown in Figure 7.

The robot cell and infrastructure were successfully tested in hot forging trials. Due to limitations in the gripper's material flow compensation, only small height reductions were applied during the forging trials to mitigate any potential risk of damage. After a pass consisting of multiple strokes, the geometry measurements were repeated to update the geometry data. If the spreading did not fit the calculated values, exciding a critical value, there was a risk of losing the calibration or damaging the robot. This issue will be addressed in future work by upgrading the gripper to one capable of better compensating for material flow, improving the overall efficiency and robustness of the forging process.

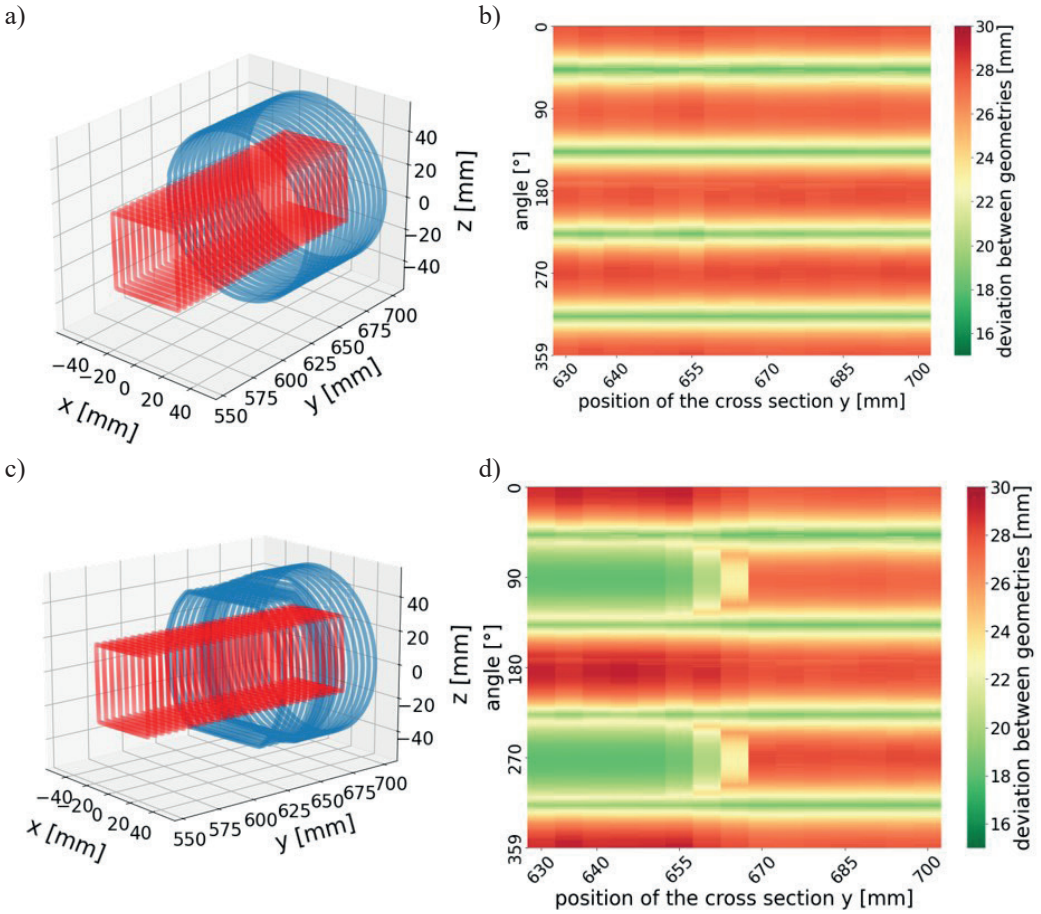

Fig. 6. Comparison of workpiece and target geometry: a) initial workpiece (blue) and target geometry (red); b) local deviation between the geometries shown in Figure 6a, represented in a polar coordinate system; c) workpiece (blue) and target geometry (red) after one press stroke; d) local deviation between the geometries shown in Figure 6c, represented in a polar coordinate system

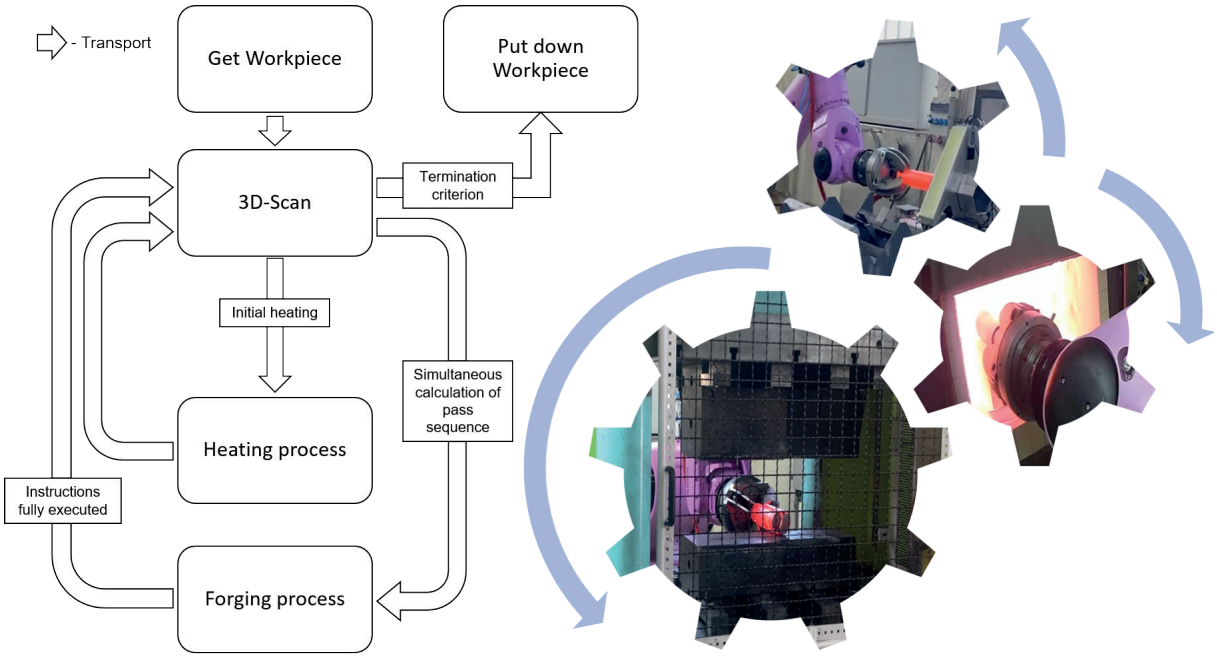

Fig. 7. Tested pass sequence planning

5. Conclusion

This study details the design and implementation of a digital infrastructure for autonomous open-die forging. The architecture employs a modular approach, with a core module serving as the central integration point, allowing for independent component modification and upgrades. One of the key challenges encountered was integrating diverse systems and interfaces into a functional solution, which was addressed through hardware and software modularity.

A process planning tool was developed that can calculate the pass sequence online, based on measurement data collected during the forging process. This application was successfully tested in practice, demonstrating the potential capabilities of the system.

Despite challenges regarding press integration, the lack of force-torque control in the robot, and gripper limitations, the system was able to achieve a functional robotic cell concept. This provides a solid foundation for future advancements, including the integration of alternative forging tools, technology-driven pass sequence planning, and the application of AI.

6. Future work

While the presented work demonstrates the feasibility and potential of the proposed digital infrastructure for an autonomous forging cell, several aspects still need to be investigated in order to fully realize an autonomous open-die forging process. Beyond the robot's ability to compensate for material flow, further research is required to address additional challenges and extend the current system towards a fully integrated and adaptive solution.

For instance, the use of fast computational models – particularly for material flow prediction – is essential for enabling online process planning. The currently used spreading model has not yet been validated, making its verification a key research objective to ensure precise and reliable process planning. In addition, material-specific model coefficients must be either determined in advance or generated automatically by the forging cell.

One important focus is the development of a deterministic state machine for the robot cell's control system, including a robust error-handling mechanism in case individual components fail to function as expected. Furthermore, the integration of additional measurement systems is planned. Since geometry and temperature data are currently acquired only through offline measurements, it would be beneficial to enable at least local, real-time updates of the digital twin during the forging process. This does not require full-field geometry or temperature mapping, but rather selective updates.

Finally, the development of a comprehensive data model is envisioned, combining workpiece information, pass sequence planning, and press log data. This unified model will provide a detailed digital representation of each forging process and serve as a foundation for building advanced, real-world datasets for future machine learning applications.

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