Digital-twin-based monitoring and simulation of robot kinematics for clay printing

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ABSTRACT: Earth-based additive manufacturing (AM), also known as clay printing, has the potential to render earth construction more efficient than existing approaches. However, issues arising from the unaccounted kinematic effects of clay printers remain unsolved, affecting the quality of printed components. To advance clay printing, further efforts are required towards investigating robot kinematics in printing processes by deploying digital twinning concepts. In this paper, a digital-twin-based framework is proposed to investigate the influence of robot kinematics on printing processes, enabling monitoring and simulation of clay printers and printing processes. The digital-twin-based framework is implemented for a clay printer consisting of a robotic system and a linear ram extruder, and it is validated by monitoring and simulating printing processes of a wall-like test structure. The results indicate that the kinematic effects arising during printing processes can be mitigated by the proposed digital-twin-based framework, serving as a basis for autonomous clay printing.

1 INTRODUCTION

The architecture, engineering, and construction (AEC) industry is moving towards more environmentally friendly, sustainable practices to address the challenges posed by climate change (Peralta & Smarsly 2022). Sustainable practices range from diminishing waste to implementing local, reusable, or recycled materials (Guido Araújo et al. 2000). By utilizing eco-friendly materials, such as earthen materials, the AEC industry may be directed towards sustainability. Environmental benefits associated with earthen materials include reducing the carbon footprint, reducing waste, and recycling materials (Pacheco-Torgal & Jalali 2012).

Earth-based structures use earthen materials as main structural materials, such as clay, and are the result of cost-effective, sustainable construction practices. However, technical difficulties in earth construction limit the transition of traditional earth construction into digital construction (Perrot et al. 2018). To advance the digitalization of earth construction, principles of earth construction may be coupled with principles of additive manufacturing (AM) and smart sensing technologies, taking advantage of the expertise gained in other branches of AM, such as concrete printing (Smarsly et al. 2020).

The potential of earth-based AM within the AEC industry has been showcased by projects and prototypes, as reviewed in (Wolf et al. 2022). More detailed studies evaluating earth-based AM have been carried out focusing on hardware solutions for extruders (Gomaa et al. 2021a), material development for optimized rheological behavior (Perrot et al. 2018), structural performance of components (Gomaa et al. 2021b), and process enhancement deploying parametric toolpath planning and extrusion control (Peralta et al. 2020). Furthermore, material extrusion is the AM technique commonly adapted to earth-based AM, using AM systems based mainly on robotic systems, similar to the AM systems used for concrete printing (Kontovourkis & Tryfonos 2020).

AM systems, commonly known as “printers”, comprise robots, extruders, and material feeders. AM systems can broadly be classified as stationary robotic systems and mobile robotic systems. Stationary robotic systems have fixed workspaces (e.g. gantry systems), while mobile robotic systems have mobile bases that allow variable workspaces (e.g. mobile robots). AM systems aim for precise material deposition, where marginal deviations in position or orientation may lead to printing issues (Dörfler et al. 2022).

Although AM, and clay printing in particular, is a research field of increasing relevance, limited attention has been directed toward the influence of kinematic effects on the accuracy of AM systems in clay printing. Unaccounted kinematic effects, such as jerk motions and vibrations, might result in deviations in the position and orientation of the extruders as well as in the continuity of material deposition, hindering the quality of the printed components (Dai et al. 2020). Hence, further efforts are needed towards investigating the effects of robot kinematics in printing processes. From process-material interactions to process control, robot kinematics are key to define robot behavior, boundary conditions, process parameters, and control strategies. Existing approaches in clay printing require long trial-and-error processes to ensure efficient process control before high quality printed components may be obtained. Digital twinning in clay printing can further the understanding of robot kinematics to help mitigate issues that may arise in printing processes.

In this paper, a digital-twin-based framework is proposed and implemented to investigate the influence of robot kinematics on printing processes in clay printing. Digital twins are virtual counterparts of physical entities, the "physical twins" which are synchronized to reflect the state of the physical entity (Tao et al. 2018). Here, digital twins are deployed for monitoring and simulation of clay printing, mirroring clay printers to identify and mitigate printing issues due to kinematic effects. The digital-twin-based approach is implemented and validated for a clay printer, where a digital twin (DT) is developed using a physics-based approach to integrate geometry models, multibody models, and kinematic models.

The remainder of this paper is organized as follows. The DT-based framework for clay printing is described and implemented for a representative clay printer in Section 2. The DT-based framework is validated in Section 3, where simulations of printing processes are performed to digitally represent the motion of the clay printer under varying printing conditions and to identify potential issues in printing processes that may be caused by kinematic effects. Finally, the main results and conclusions of the study are summarized, and a brief discussion of the limitations and potential future directions is presented.

2 A DIGITAL-TWIN-BASED FRAMEWORK FOR CLAY PRINTING

This section provides an overview of the DT-based framework for clay printing. The DT-based framework is implemented for a clay printer, a 3-degrees-of-freedom (DOF) SCARA robot. As will be shown, the digital twin is used to investigate kinematic effects of the clay printer on the printing process, by providing monitoring and simulation services.

The DT-based framework proposes a DT concept to enable monitoring and simulation of clay printing processes, digitally representing the motion of clay printers, and identifying potential issues in printing processes that may be caused by kinematic effects. Monitoring and simulation of robot movements aids the identification of deviations in the position of extruders from predefined trajectories that may hinder material deposition. By evaluating the deviations in extruder position, it is possible to mitigate issues due to kinematic effects in printing processes during the design and planning of printing projects. This paper focuses on identifying points of increased vibration and jerk motions in printing processes, predicting related issues, and defining control strategies to mitigate printing errors.

Digital twins for clay printers are conceptualized based on a reference DT architecture previously proposed by the authors (Smarsly et al. 2024). The DT uses a layered, service-oriented system architecture to represent the functionalities and behaviors of clay printers (i.e. physical entity) in a digital environment, as shown in Figure 1.

Figure 1 illustrates the system architecture of the DT, comprised of a presentation layer, a platform layer, a data acquisition layer, and a transmission layer. The *presentation layer* contains a user interface that enables user interaction with the digital twin. The *platform layer* encompasses the digital representations of the clay printers, services for monitoring and simulation, and data storage. The digital representations include geometric models, multibody models, and kinematic models. The monitoring service oversees the system performance and status throughout the simulation. The simulation service executes simulations employing models and process-related data to accurately replicate the behavior of the clay printer. The *data acquisition layer* collects data from the clay printer and sensors, and the *transmission layer* enables communication between the layers.

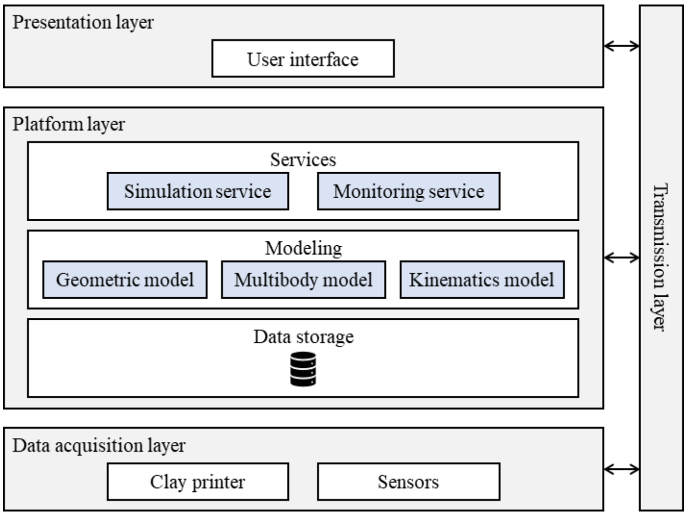

Figure 1. System architecture for the digital twin for clay printing.

2.1 *A digital twin for clay printers*

Clay printers in this study are represented as robots using the standardized Denavit-Hartenberg (DH) convention and are modeled digitally using a physics-based approach. The positions of individual joints of the robots are estimated using a numerical solution to the inverse kinematics problem, utilizing a numerical solver based on the Levenberg-Marquadt algorithm, while proportional-integral-derivate (PID) controllers are utilized to adjust process-related parameters according to the behavior of the robot.

The digital twin for the 3-DOF SCARA clay printer is implemented using MATLAB and Simulink (MathWorks 2024a) as a modeling and simulation tool. A geometric model of the clay printer is used to generate a multibody model to represent the components and the physics-based interactions between the components of the robotic system, resulting in a rigid body tree robot model. In addition, a kinematic model is derived considering the robot model and joint positions based on DH parameters of the robot (Denavit & Hartenberg 1955). By integrating the robot model into the simulation environment model, monitoring and simulation services are developed. The services replicate the motion of clay printers for user-defined trajectories and process-related parameters (e.g., print speed and material payload) using PID controllers to adjust the behavior of the clay printer based on a feedback loop for the joint positions. In the following subsections, an overview of the robot model, the kinematic model, and the simulation service is presented.

2.1.1 *Robot model*

The 3-DOF SCARA clay printer has three joints (Figure 2), two revolute joints (J_1 and J_2), and a prismatic joint (J_3). The first revolute joint J_1 is located at the base of the robot and can rotate around θ_1 in the range between 0° to 360°. The prismatic joint J_3 is connected to the vertical rail, positioned directly above revolute joint J_1 at the base, and is capable of vertical motion up to a maximum height (d_1) of 1.03 m. Two robot links are connected by the second revolute joint J_2 and attached to the prismatic joint J_3. The second revolute joint J_2 has a rotation range between 0° to 180°, i.e. from completely stretched out to a fully retracted state. The extruder is controlled by a linear actuator ram that extrudes the clay for deposition.

2.1.2 *Kinematics model*

The kinematics of the clay printer are defined using the DH convention to determine the parameters for modeling links and joints, from the base (*position* 0) to the extruder (*position E*). Accordingly, the DH parameters are determined as shown in Table 1. To estimate joint configurations of the robot to follow a target printing path of the extruder, a numerical solution to the inverse kinematics problem is calculated. The numerical solution involves solving a numerical optimization problem that utilizes an iterative process to determine joint positions that allow the end-effector to converge to the required pose (i.e. extruder pose) by minimizing the difference between the target end-effector pose and the current pose. The Levenberg-Marquadt algorithm is selected as the numerical solver for the inverse kinematics solution as it is expected to converge faster than other numerical methods when used along predefined trajectories of the extruder (MathWorks 2024b). In contrast to the analytical solution to the inverse kinematics problem, the use of a numerical solver provides a robust solution and avoids robot singularities (Sugihara 2011).

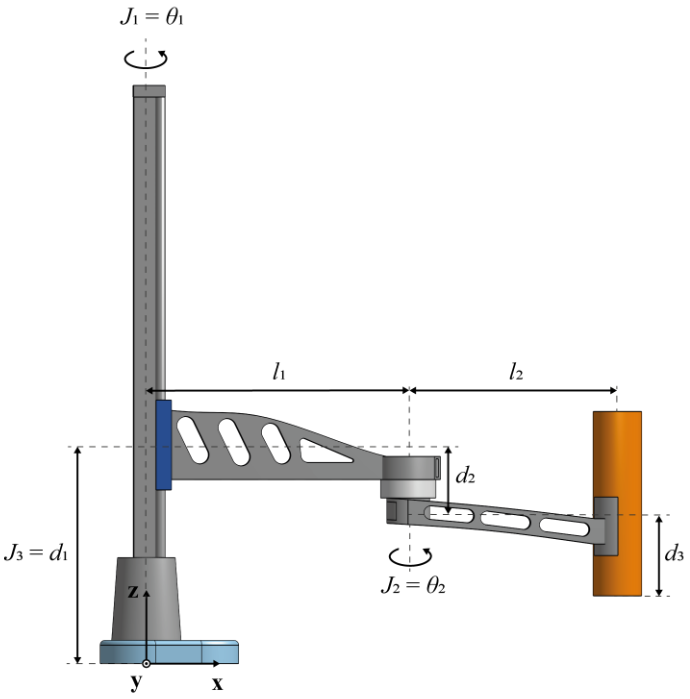

Figure 2. Multibody model of the SCARA clay printer, including link and joint assignments.

Table 1. Denavit-Hartenberg parameters for the SCARA clay printer.

Position/joint	α_{i-1}	a_{i-1}	d_i	θ_i
0	0	0	0	0
1	0	0	0	θ_1
2	0	0	d_1	0
3	±180°	l_1	0	θ_2
E	0	l_2	$d_2 + d_3$	0

2.1.3 *Simulation service*

The simulation service is deployed using the Simscape simulation tool within Simulink, as shown in Figure 3. To simulate the motion of the clay printer, the simulation service uses target trajectories, target end times, and material payload as inputs. The target trajectories are defined as a vector of target points $\boldsymbol{p}_i = (x_i, y_i, z_i)$ representing the coordinates of the extruder. From the target print speeds, discretized time steps are assigned to each target point, and a trapezoidal velocity profile is generated. The inverse kinematics block numerically solves the target trajectory into estimated joint positions (θ_1, θ_2, d_1). The estimated joint positions are fed into the PID controllers, which convert the joint positions into process-related parameters for torque and force. The torque and force parameters are used to predict the behavior of the clay printer expressed as output trajectory, output velocity, output acceleration, and output torque. To refine the simulation, a feedback loop is deployed to return actual join positions, which are derived from the output trajectory, to the PID controllers. Points of increased vibration and jerk motions are identified as peaks in the output torque and output velocity, respectively. In the following section, the validation of the DT-based framework is presented.

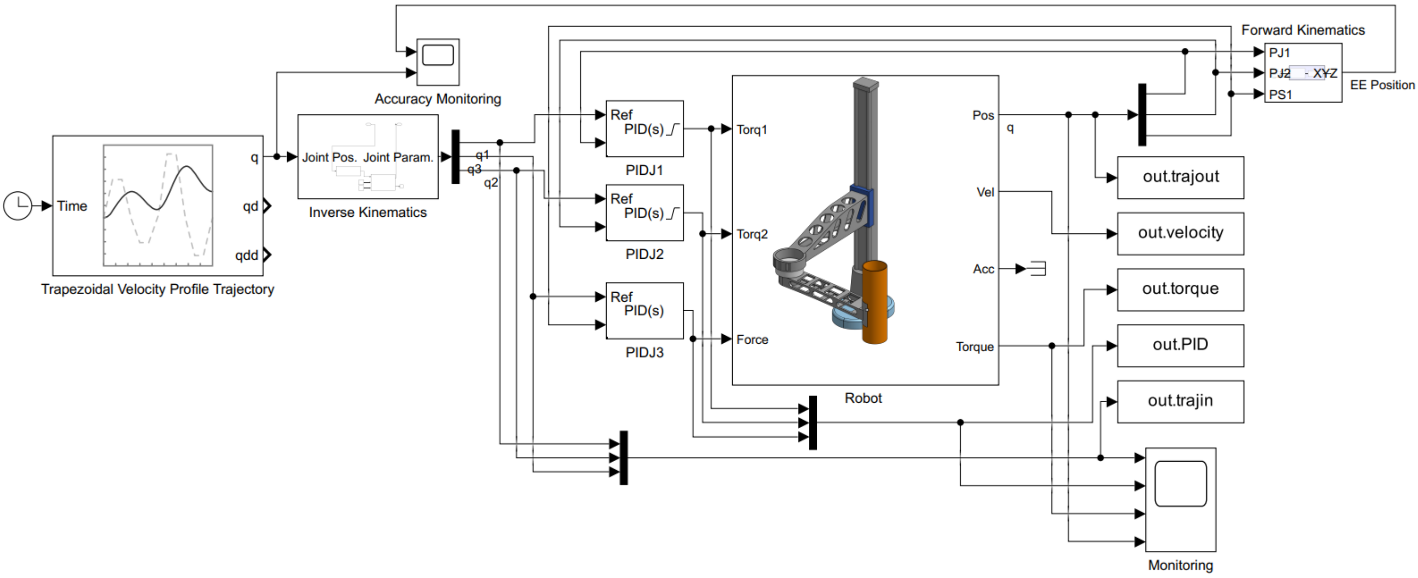

Figure 3. Simscape simulation architecture.

3 SIMULATION OF ROBOT KINEMATICS FOR CLAY PRINTING

This section describes the validation of the DT-based framework. To evaluate the suitability of the digital twin for identifying issues that may be caused by kinematic effects, it is essential to assess the correctness of the outcomes of the simulation. Therefore, an illustrative case study is defined for validation, where the printing process of a wall-like test structure is monitored and simulated considering various printing scenarios and control strategies.

3.1 *Case study*

The case study describes the printing process of a test structure consisting of a rectangular wall element with a jagged inner structure. The printing process for each layer is divided into three steps, namely perimeter structure, infill structure, and layer transition. First, the perimeter structure of the wall is printed by depositing material along the outline of the wall. Second, the infill structure of the wall is printed, where material is deposited along the jagged inner structure providing stability. Third, the extruder moves back to an initial position while transitioning to the next layer and moving the extruder to the subsequent layer height. The process is repeated until printing of the wall element has been completed. According to the printing process, a target printing path is defined per layer.

3.2 *Results*

The target printing path for the wall element is defined as a target trajectory for the simulation, as shown in Figure 4, with a target print speed of 0.1 m/s. To investigate potential changes in accuracy during the printing process, the material payload on the extruder is varied throughout the simulation process. The relationship between process-related parameters and the material payload, including related kinematic effects, is one of the primary uncertainties for the SCARA clay printer. To study the relationships between the parameters, four printing scenarios with varying material payloads are introduced. The material payload starts at full extrusion capacity and is decreased by one-third of its capacity in every scenario until the extruder has been completely emptied. Therefore, the four printing scenarios, corresponding to material payloads at 100%, 66%, 33% and 0%, are compared in subsequent simulation results.

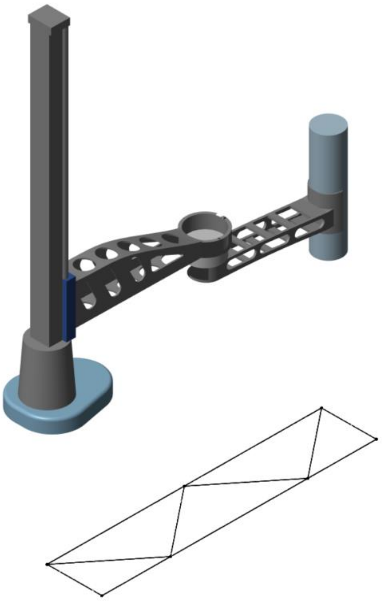

Figure 4. Simulation environment and target trajectory.

The real printing path, i.e. output trajectory, is observed and shown as an error tracking graph for every joint (Figures 5 and 6). The error for each joint position is subsequently compared across simulations with varying material payloads spanning 100%, 66%, 33% and 0% of the material payload. The results indicate that the model of the clay printer tracks the target printing path with only minor errors. It is observed that initial deviations arise due to the settling time associated with the PID controllers. Furthermore, errors are comparatively reduced at the corners of the printed structure with the reduction of the material payload. In addition, it can also be observed that the output torques across simulation experiments decrease, especially at their peaks (Figures 7 and 8) and output velocities remain closely aligned during simulation experiments (Figures 9 and 10). Comparatively, the output force for joint J_3 decreases due to decreasing material payload in the extruder, however, errors across the entire simulation are negligible (Figure 11).

Results from experiments performed within the simulation environment indicate that estimated joint positions for the joints of the clay printer successfully track the target trajectories with minimal deviation. The simulation environment exhibits real-time performance and latency-free estimation of joint positions, while also displaying robustness against robot singularities. The results thus validate the implemented simulation system for further experiments using real-world data, to evaluate extrusion rate errors from the simulation data, and to define control strategies.

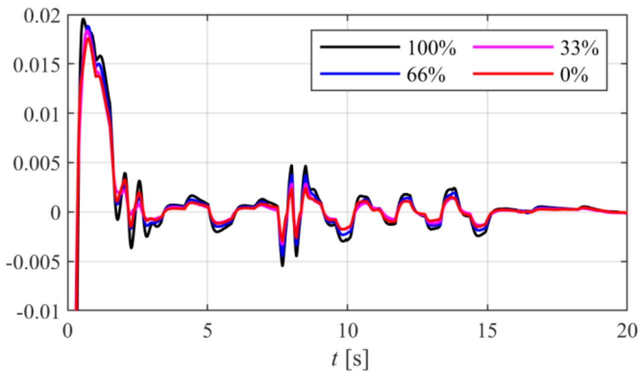

Figure 5. Error tracking for the position of joint J_1.

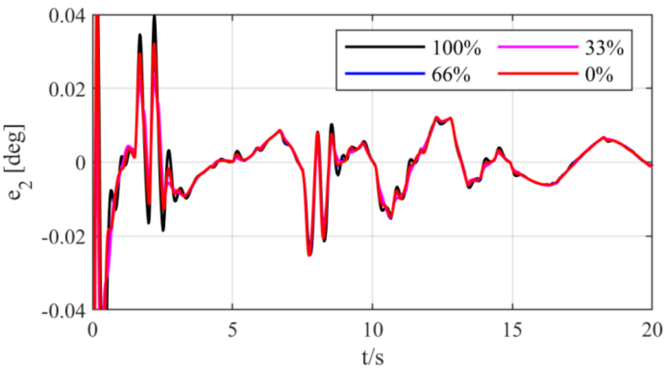

Figure 6. Error tracking for the position of joint J_2.

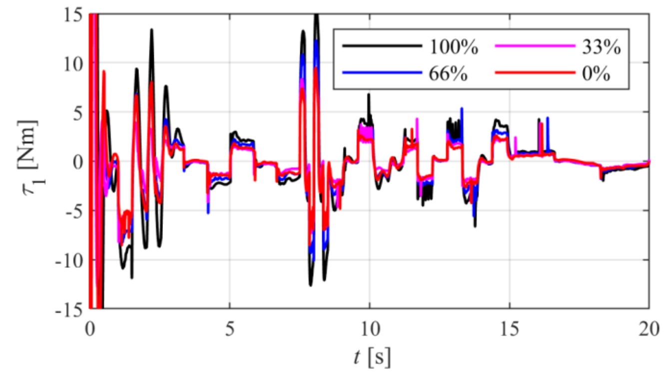

Figure 7. Output torque of joint J_1.

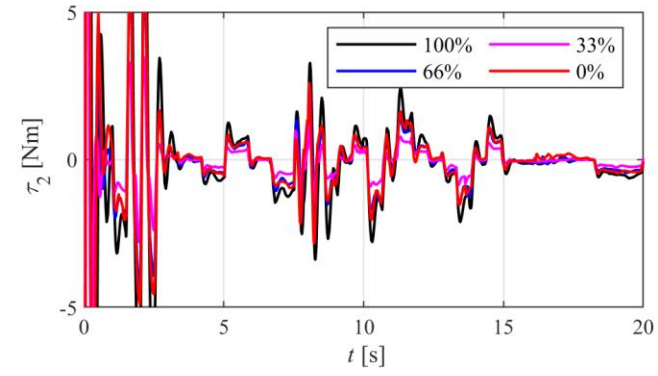

Figure 8. Output torque of joint J_2.

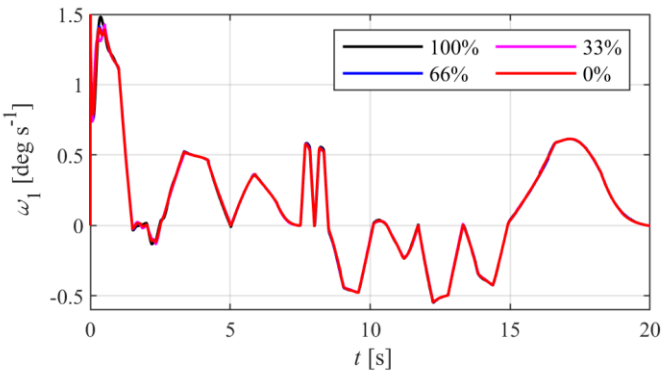

Figure 9. Output angular velocity of joint J_1.

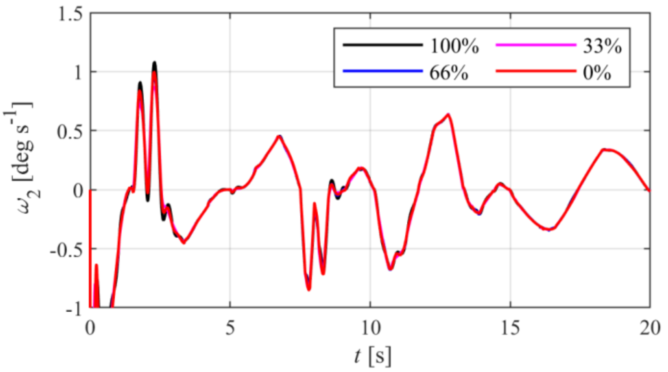

Figure 10. Output angular velocity of joint J_2.

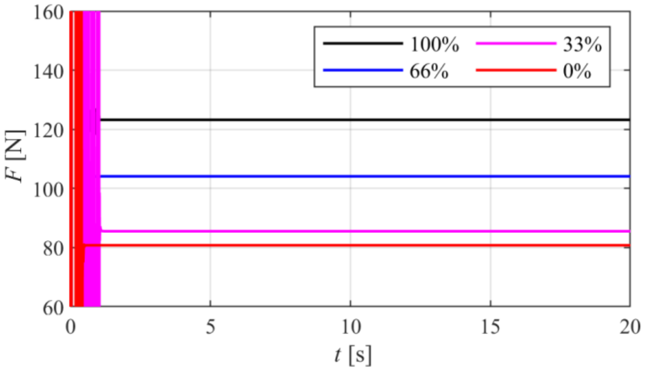

Figure 11. Output force of joint J_3.

4 SUMMARY AND CONCLUSIONS

In this paper, the influence of robot kinematics on clay printing processes has been investigated using a digital-twin based approach. A digital twin has been developed to replicate the motion of clay printers, thereby identifying printing issues caused by kinematic effects as well as validating the print path planning. For validation, a 3-DOF SCARA clay printer has been exemplarily used, simulating the printing process of a wall-like test structure.

The digital twin concept has been implemented using modeling and computing tools for modeling the geometry, the multibody system and the kinematics of the SCARA clay printer. As input parameters, the simulation service provided by the digital twin uses inverse kinematics to replicate robot motions using target trajectories, target print speeds, and material payload on the extruder. A graphical user interface allows inputting parameters for the simulation as well as visualizing the data generated by the simulation, such as animations and plots. The validation has been performed on a rectangular wall element with a jagged internal structure, considering varying material payloads. Comparative curves have been used to display the results obtained from the simulation. It has been observed that the accuracy of the clay printer improves as the material payload decreases during the printing process due to material deposition. The results display the viability of the approach used for modeling a SCARA clay printer. The model exhibits a robust and fast simulation environment that can be used to facilitate the optimization of kinematic deviations.

In conclusion, issues arising from the robot kinematic of the robot can be mitigated by evaluating printing parameters via simulations of the printer movements by generating appropriate printing strategies. The validation has been conducted on a test structure where kinematic effects caused by vibrations and jerk motions are expected, e.g., showcasing increased error rates at sharp corners. However, limitations are observed in the simulation service provided by the digital twin, as sensor data from the SCARA clay printer is needed as inputs to further analyze the tradeoff between printing accuracy and print speed. In future work, the research may be extended towards developing DT services for real-time monitoring and device control in clay printing to archive adaptive printing.

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