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DIGITAL TWIN VIRTUAL APPROACH OF ROBOT BASED INCREMENTAL SHEET-METAL FORMING PROCESS

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Abstract: *This study aims to develop and qualitatively validate a digital twin of an incremental sheet-metal forming (ISMF) system using a KUKA KR 210 industrial robot. Leveraging Industry 4.0 principles, the digital twin integrates physical and virtual components to enhance manufacturing efficiency and performance. The research outlines an experimental setup for robotic incremental forming, employing dynamic modeling and toolpath using MATLAB-Simscape-Multibody. The study investigates kinematics, toolpath, forming forces, and dynamic modeling of the robot. Results demonstrate the feasibility of the proposed approach, enabling real-time monitoring, predictive maintenance, and quality assurance in ISMF processes, contributing to advancements in intelligent manufacturing.*
Key words: *Digital Twin, Incremental Sheet-Metal Forming, Single Point Incremental Forming, Industrial robot, Robot dynamics, Forming forces.*

1. INTRODUCTION

The fusion of virtual and physical realms lies at the core of Industry 4.0 and drives future innovation [1]. As a fundamental component of Industry 4.0, the digital twin has garnered significant interest from academia and industry worldwide, emerging as a novel research domain [2, 3]. Origins of digital twin traced to NASA's Apollo project and US Air Force; concept formalized by Michael Grieves in 2002, comprising physical and virtual products linked by data flow [4, 5].

The digital twin involves the integration of physical objects with virtual counterparts that mirror the functionality of real machinery. It plays a pivotal role in enhancing efficiency, optimizing production cycle times, bolstering production flexibility, and enhancing the overall performance of intelligent manufacturing processes [6 - 8].

The rise in demand for customized products has been spurred by the gradual evolution of smarter forming techniques, like ISMF, pioneered by Leszak in 1967 [9]. ISMF encompasses Single-Point Incremental Forming (SPIF) and Two-Point Incremental Forming (TPIF), both optimized by researchers for economical and high-quality production. SPIF involves incremental punch movement over a clamped sheet to deform it, while TPIF employs specially designed fixtures for enhanced precision and material deformation. Considering the simplicity of the kinematics involved in the ISMF process, it can be performed on various industrial equipment such as specialized machines, CNC milling machines, industrial robots [10]. The ISMF process is inherently slow, but an industrial robot's high-speed movement capability can offset this drawback [11 - 13]. Furthermore, the robot's flexibility allows for the precise production of complex-shaped parts. In a recent synthesis article, Kumar et al. [14] provide a detailed overview of the diverse applications of the incremental forming process. Through this synthesis, they offer insights into the potential applications of incremental forming, such as those in the aerospace industry, automotive manufacturing, biomedical applications, and more.

In the realm of ISMF processes, digital twins offer significant advantages. They enable simulation, real-time monitoring, predictive maintenance, and quality assurance, optimizing

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manufacturing operations. By simulating the forming process, fine-tuning parameters, and monitoring real-time data, manufacturers can enhance efficiency, ensure product quality, and reduce downtime.

However, there are relatively few papers that address the concept of digital twin in the context of a incremental forming processes [14, 15]. Therefore, this paper presents the development of a digital twin for a SPIF process based on industrial robot as industrial equipment.

2. MATERIALS AND METHOD

The study outlines an experimental setup for robotic incremental forming, employing a KUKA KR210. Based on MATLAB – Simscape - Multibody it was developed the dynamic model of the robot. Constraints were introduced into the Simscape model to simulate the functionality of the robot, which was constructed based on a 3D model imported from Solidworks. Toolpath generation was done using SprutCAM software, with CAM-generated code input into the inverse kinematic function block. The model calculated torques within robot joints based on joint angle values and forming forces measured by an external force transducer.

2.1 Kinematics of KUKA KR210

In order to program the KUKA KR210 robot along a toolpath defined by the user, the kinematic problem was addressed first. Starting from the theoretical foundations related to the kinematics of robots with serial topology, the solution to the robot's kinematic problem was analyzed. The robot's kinematics involved developing specific mathematical equations characteristic of the robot's structure. Solving the kinematic problem is related to the connection between relative displacements in the kinematic joints, the positions of kinematic elements, and the absolute poses of the punch. These mathematical relationships are applied in two consecutive phases: addressing the direct kinematic problem and tackling the inverse kinematic problem [16, 17].

Direct kinematics (DK)

The direct kinematics of the KUKA KR210 were established by incorporating the Denavit-Hartenberg parameters. This involved deriving homogeneous transformation matrices for each kinematic link and robot joint, encompassing the entire robot structure. By employing Euler angles, the orientation of the punch relative to the robot base was determined. The kinematic configuration of the KUKA KR210 is depicted in Figure 1.

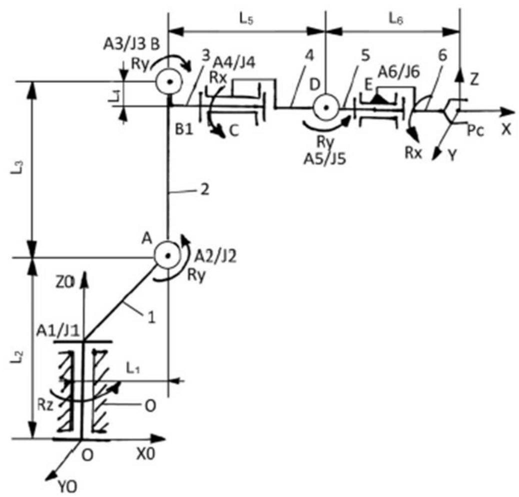


Fig. 1. Kinematic diagram of KUKA KR210 robot

Inverse kinematics (IK)

Solving the inverse kinematics for KUKA KR210 entails deducing the relative movements in each kinematic joint using the known absolute poses of the punch. Given the mechanical configuration of the KUKA KR210, an analytical solution to the inverse kinematics problem was viable, leading to the adoption of a geometric approach for resolution. To validate the robot's kinematic model, a Simulink diagram was constructed, as shown in Figure 2. The input data for the "DK" block are values of the joint angles, from which absolute values for the poses of the punch are determined. If the output values from the "DK" block are used as input data for the "IK" block, this block will provide the values of the joint angle.

The obtained results indicate a close match between the toolpath data generated through CAM program and the verified toolpath data calculated by the Simscape model.

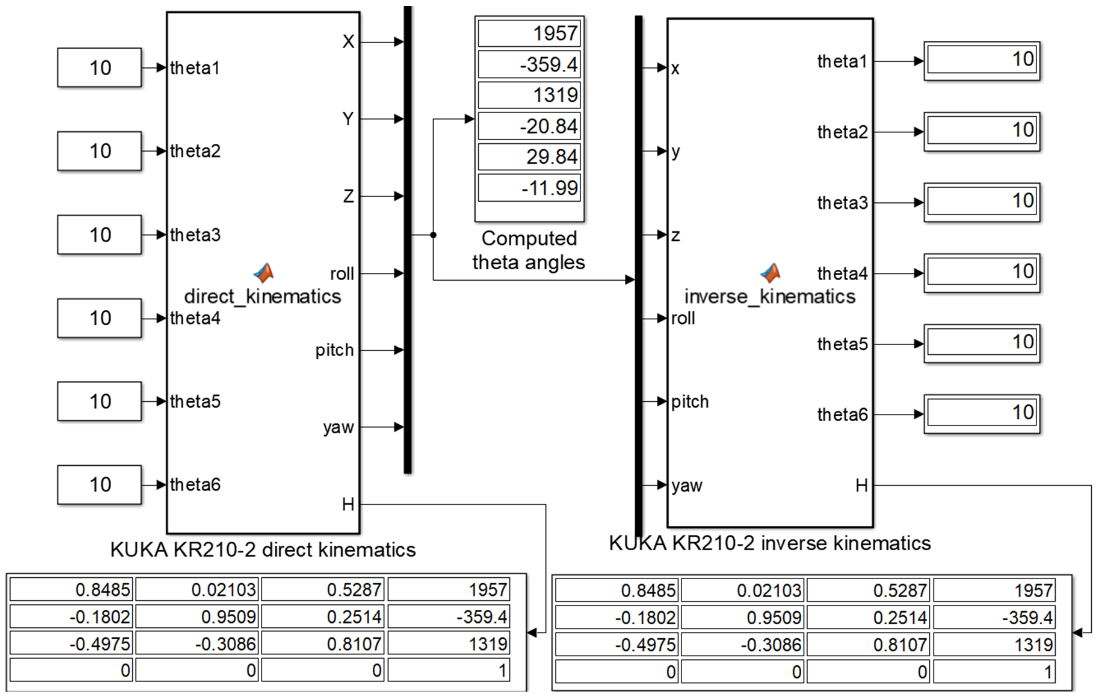


Fig. 2. KUKA KR210 kinematic validation

2.2 Toolpath planning

Even though there is no dedicated CAM software package for the ISMF process, the coordinates of the points on the trajectory can be calculated in both machining and incremental forming scenarios, as the reference point is the tool tip. The main disadvantage is the inability to run a real simulation of the ISMF process because CAM packages consider the cutting edges of the tool and the machining strategy. However, for now, it can be stated that the specific steps of the machining process based on CAM solutions can be used in the case of ISMF processing as well.

The code for guiding the punch along the processing toolpaths while ensuring collision avoidance and singularity avoidance was produced using SprutCAM software. The 3D model of the sheet fastening system, along with the kinematic model of the KUKA KR210, represents the required data for generating the forming-related code.

The kinematic model of the robot is based on a specific template for KUKA robots, provided by SprutCAM, and is saved in .xml format. The sheet fastening system was designed and manufactured to fix the metal sheet, ensuring its free forming during the ISMF process. The system comprises a retaining frame fixed onto a support frame, a support plate, and the metal sheet itself. In figure 3 is illustrated the kinematic model of the KUKA KR210 alongside the sheet fastening system, serving as digital twins of the system.

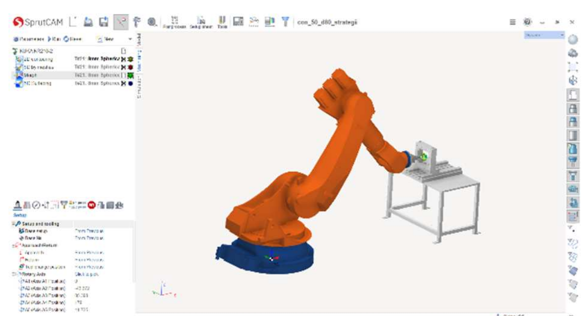


Fig. 3. Digital twin of the developed system.

2.3 Forming forces

It is essential to comprehend the values of the forces applied to the robot end-effector during the SPIF process before developing the dynamic model. Precisely estimating the maximum forming forces is essential for guaranteeing the secure operation of the developed forming system. Moreover, the energy consumption during the process is affected by the force values.

Using the PCB 261A13 force transducer it was possible to measure the real values of the forming forces. During the SPIF process, the electrical signals were amplified via HBM PACEline CMD 600 digital charge amplifier, which was then transmitted to the data acquisition system, namely HBM QuantumX MX840B model. This setup facilitated the measurement of the forming force components (Fx, Fy, Fz). For data acquisition, visualization, and analysis purposes it was used the Catman software. The actual values of the forming force components were determined by correlating the received electrical signals with the force magnitudes using calibration curves.

2.4 Dynamic model of the KUKA KR210 robot

KUKA KR210 dynamic model was developed in the Simulink – Simscape Multibody environment.

Firstly, the CAD model of KUKA KR210 was imported into the Simscape – Multibody. This provided high accuracy representation of the mechanical properties of the real robot, considering all the data, such as mass, links dimensions, coordinate systems, moment of inertia. Once the 3D model was converted to Multibody system, the robot based developed assembly was represented using characteristic blocks.

To simulate the dynamic behavior of the robotic structure, various elements such as actuators and sensors were added to the simulation diagram, as illustrated in Figure 4.

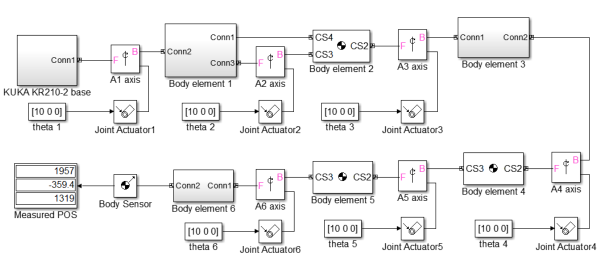


Fig. 4. Simscape Multibody robot system diagram

3. RESULTS

The experimental setup, shown in Figure 5, comprises the industrial robot KUKA KR210, the sheet fastening system, the PCB 261A13 force transducer, and the data acquisition system.

Fig. 5. Experimental layout for SPIF.

To analyze the presented approach, the experiments involved a truncated cone shape part. The parameters of the truncated cone shape part are as follows:

- Wall angle: 50º;
- Height: 30 mm;
- Big radius: 40mm;
- Material: DC04 steel.

For the incremental forming of the parts, a punch with a hemispherical head of 10 mm diameter was used. To limit the frictional force between the metal-sheet and the punch it was applied grease. As shown in Figure 6, a spiral toolpath was employed to shape the truncated cone parts. The vertical step was 1 mm. The spiral toolpath was implemented to reach a uniform distribution of stresses across the part surface and decrease the risk of lead-in and lead-out defects. Such defects can serve as stress concentrators, potentially causing crack deformation.

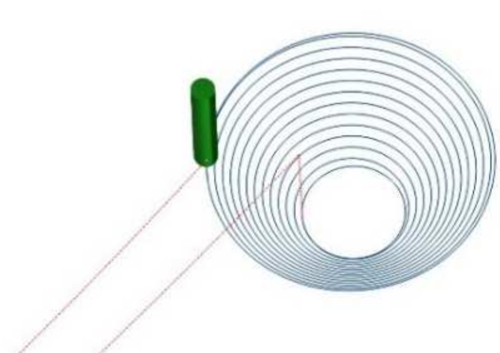
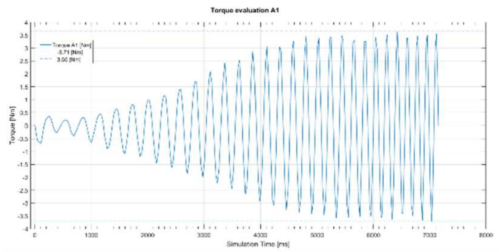
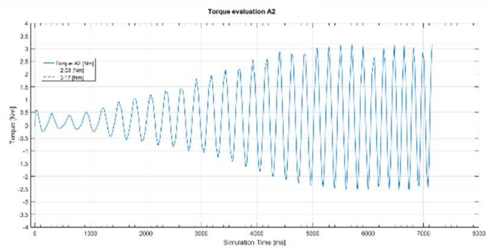


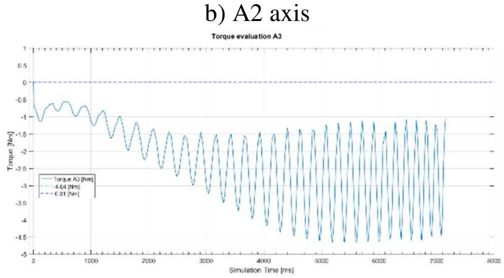
Fig. 6. Toolpath used in experimental research.



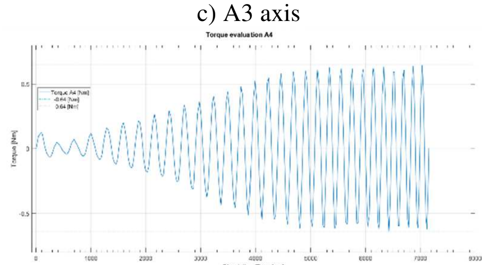
a) A1 axis



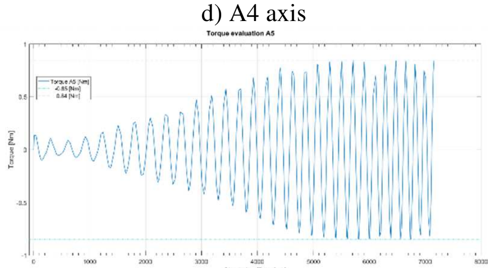
b) A2 axis



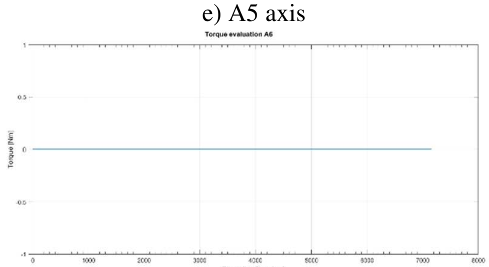
c) A3 axis



d) A4 axis

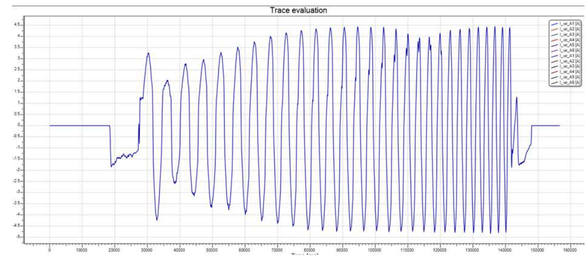


e) A5 axis

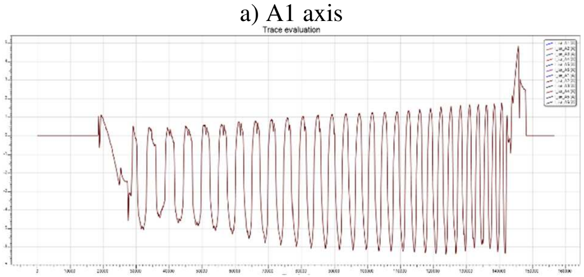


e) A6 axis

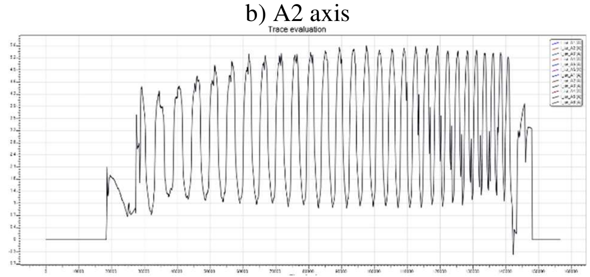
Fig. 7. Differential joint torques for each axis.



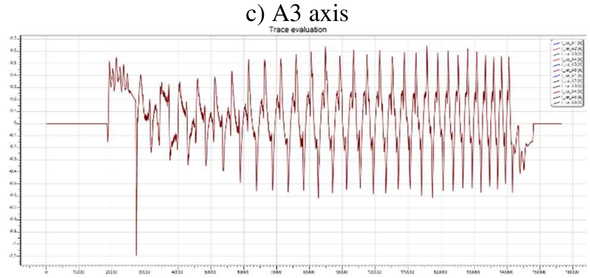
a) A1 axis



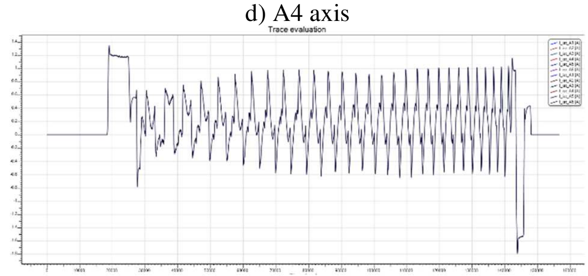
b) A2 axis



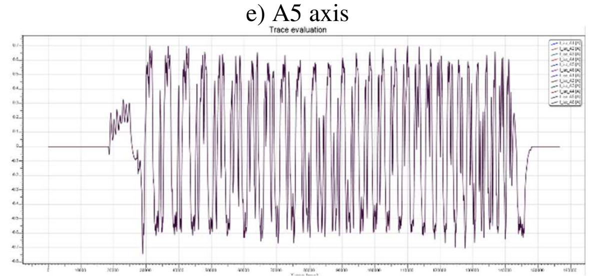
c) A3 axis



d) A4 axis



e) A5 axis



e) A6 axis

Fig. 8. Currents through joint motors for each axis.

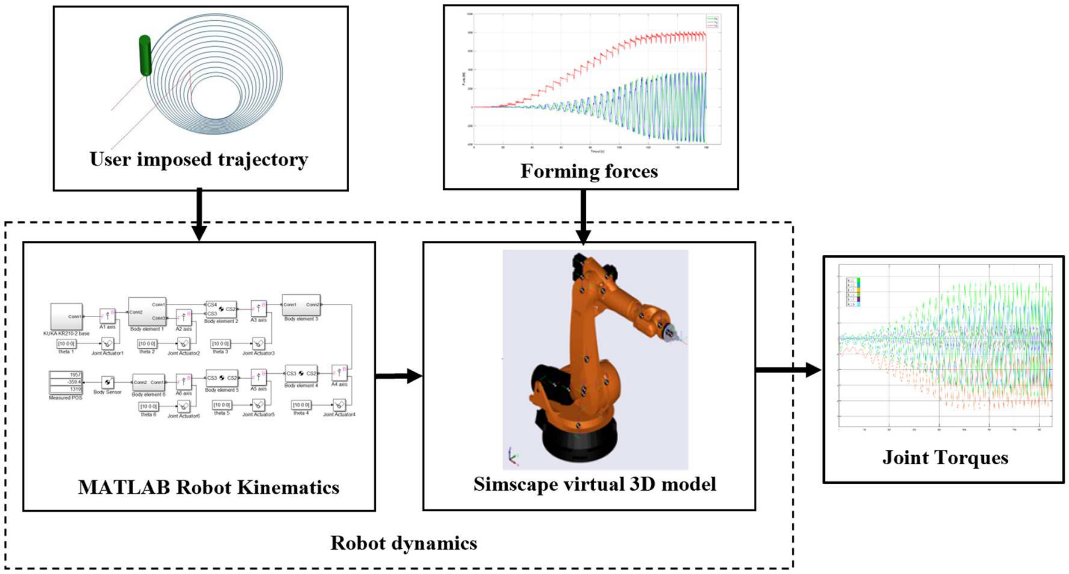


Fig. 9. Developed dynamic model of the robotic incremental forming system.

However, it's important to note that there are currently no CAM software programs dedicated to the incremental forming process. Therefore, the specific stages of the milling process were followed using CAM solutions. Consequently, the punch was replaced with a spherical mill with 10 mm diameter. This decision doesn't affect the generation of an accurate punch toolpath because the reference point is considered to be the tip of the tool. The simulation from SprutCAM depicts material removal between the workpiece and the final part, whereas in reality, material redistribution occurs. However, these acts did not impact the toolpath illustrated in Figure 6. The programming code was generated based on the absolute poses of the punch, along with the forming force values from PCB 261A13 force transducer. These inputs were utilized in the simulation diagram, as shown in Figure 9.

The joint torque values were determined based on the forming forces. Based on the relationship of interdependence between the acquired electrical signal value and the force magnitude, established by calibration curves, it was possible to calculate the actual values of the forming force components.

To establish the values of joint torques, simulations of SPIF process were executed by imposing specific toolpath. After these simulations, the joint torques were determined, as illustrated in Figure 7.

Figure 8 displays the current values flowing through the joint motors during the incremental forming process. These values were visualized using KUKA Visual Work software and utilized for the quantitative validation of the simulation results.

Table 1 synthesizes the data from Figure 7 and 8, presenting simulated joint torques (MATLAB) and measured currents through the joint motors (KUKA). Qualitatively, the variation in simulated joint torques over time mirrors that observed in the currents through the joint motors.

Table 1

Minimum and maximum values – simulation (S) vs. reality (R).

Joint axis	A1	A2	A3	A4	A5	A6
S.	-3.71 to 3.65	-2.53 to 3.17	-4.64 to 0.01	-0.64 to 0.64	-0.85 to 0.84	-0 to 0
R.	-4.83 to 4.46	-6.4 to 1.8	0.9 to 5.63	-0.61 to 0.66	-0.64 to 1.03	-0.88 to 0.88

4. CONCLUSION

The objective of this study was to develop and qualitatively validate a digital twin of an ISMF system utilizing a KUKA KR210 industrial robot.

Utilizing industrial robots in machining or forming processes with continuous path control poses challenges due to their complex mechatronic nature, notably low structural rigidity, and machining accuracy limitations. Additionally, while incremental forming suits robot use with reduced precision demands, it can induce joint torque surpassing permissible levels due to technological forces.

By integrating CAD techniques (adapting the 3D model of the robotic structure and modeling auxiliary systems and fastening devices), CAM (generating trajectories using the SpruCAM software package), and CAE (developing the dynamic model of the robotic-based technological system in Simulink-Simscape), users are provided with tools and solutions with high potential for improving the processing parameters using industrial robots, both through incremental forming and other procedures that involve continuous control of machining toolpaths, as well a reduction in dynamic demands on the robotic structure.

The proposed digital twin, developed through the integration of CAE and CAM models, allows users to program toolpaths, analyze robot kinematics, and estimate dynamic behavior, particularly joint torque values.

Further research will aim to:

- Consider the impact of robot dynamics on toolpaths and explore methods for optimizing them.
- Performing a quantitative analysis to validate the calculated values of the joint torques based on the measured currents.

5. AKNOWLEDGEMENTS

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Modelul virtual al procesului de deformare incrementală prin intermediul robotului

Rezumat: Obiectivul acestui studiu este de a dezvolta și valida calitativ o reprezentare digitală realistă al unui sistem real de deformare incrementală a tablelor subțiri folosind un robot industrial KUKA KR210. Deformarea incrementală cu robotul implică un control continuu al traiectoriei, o caracteristică disponibilă în controlerele robotice, cât și în pachetele de software CAM. Cu toate acestea, soluțiile CAM convenționale se concentrează exclusiv pe generarea codului pentru structura robotică pentru a urma traiectoria sculei, fără a lua în considerare dinamica. În acest studiu, deformarea incrementală prin intermediul robotului a fost explorată ca proces de fabricație, iar un model de simulare bazat pe un model Matlab-Simulink Simscape Multibody a fost dezvoltat. Cu ajutorul modelului dinamic dezvoltat, prin introducerea traiectoriei impuse de utilizator și a valorilor forțelor din proces, se pot determina valorile momentelor rezistente la nivelul cuplelor cinematice ale robotului în timpul procesului de deformare incrementală.

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