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IMPLEMENTATION OF USING COLLABORATIVE ROBOTS IN THE ADDITIVE MANUFACTURING PROCESS

Fănică-Valeriu Hrib[1], Florin Chifan[1], Constantin-Cătălin Dosoftei[2],

[1]"Gheorghe Asachi" Technical University of Iasi-Romania, Department of Machine Manufacturing Technology, Blvd. Mangeron, No. 59A, 700050, Iasi, Romania
[2]"Gheorghe Asachi" Technical University of Iasi-Romania, Department of Automatic Control and Applied Informatics, Blvd. Mangeron, No. 27, 700050, Iasi, Romania

Corresponding author: Constantin-Cătălin Dosoftei, constantin-catalin.dosoftei@academic.tuiasi.ro

Abstract: The manufacturing sector is increasingly integrating additive manufacturing and robotics, marking a significant evolution in production methods. This paper delves into the field of robotic-assisted additive manufacturing, highlighting the use of robotic arms to enhance the efficiency and precision of the 3D printing process. Central to this research is the adaptation of the Universal Robot UR3e model within a 3D printing system. The study confronts and resolves numerous challenges, such as selecting a suitable printing extruder, determining appropriate material types, and optimizing nozzle dimensions. Essential aspects like developing control software for the robot arm and extruder, interpreting 3D models into robotic instructions, and calibrating the hardware are examined in detail. These processes involve fine-tuning the arm's motion, optimizing material extrusion rates, and conducting comprehensive testing to ensure accuracy and quality of the printed objects. This multidisciplinary approach underlines the complexities of merging 3D printing with robotic technology, necessitating expertise across mechanical, electrical, automation, and software engineering domains. A key focus of this paper is not just the technical implementation but also the practical outcomes. Experiments were conducted to evaluate the compatibility between the G-code program and the RoboDK software, leading to the successful physical realization of the printed products. These experiments demonstrated not only the feasibility of the system but also its potential for producing high-quality, precise 3D printed objects. The results obtained underscore the effectiveness of the integrated system in actual manufacturing scenarios, paving the way for advanced applications in robotic-assisted 3D printing.
Key words: robotic-assisted additive manufacturing, collaborative robot, 3D printing technology, automation in manufacturing

1. INTRODUCTION

The emergence of Industry 4.0 signifies a paradigm shift in the manufacturing sector, characterised by the integration of digital technologies, automation, and the flow of data, which collectively redefine the industry landscape. The fourth industrial revolution is distinguished by incorporating cutting-edge technologies, including the Internet of Things (IoT), cloud computing, Artificial Intelligence (AI), and robotics, [1]. This convergence ushers in a new era of intelligent manufacturing systems. These advancements do not solely serve as technological improvements; they signify a profound transformation in the approach to designing, manufacturing, and distributing products. They provide unparalleled levels of efficiency, customisation, and quality.
One of the cores of this technological revolution lies in the rise of additive manufacturing (AM), more generally referred to as 3D printing. The utilisation of this method, which systematically builds items in a sequential manner based on a digital representation, has significantly transformed the prevailing manufacturing frameworks. This advancement has facilitated enhanced flexibility in design, minimised material wastage, and enabled the economical fabrication of intricate geometries. The significance of this phenomenon extends beyond the realm of industrial processes, as it poses challenges to conventional supply chain models and redefines the notion of product life cycles.
Concurrently, the domain of robotics has experienced notable progressions, transitioning from conventional, solitary industrial robots to exceedingly intricate, cooperative systems [2]. Collaborative robots, sometimes called cobots, have been specifically engineered to operate in conjunction with human labourers, augmenting their skill sets and optimising both efficiency and safety within the workplace. In contrast to previous models, collaborative robots, commonly known as cobots, have attributes such as adaptability, user-friendly programming interfaces, and the ability to operate with humans safely. These qualities render them highly suitable for a diverse array of

tasks, including those within the domain of additive manufacturing.
Integrating cobots in the confluence of additive manufacturing and robotics has given rise to a novel concept known as robotic-assisted additive manufacturing (RAAM). Integrating robotics and 3D printing in the form of RAAM results in a collaborative fusion that combines the accuracy and consistency of robotic technology with the adaptability and inventive potential of 3D printing. The integration of this technology holds the potential to facilitate advancements in the manufacturing sector, including the automation of intricate manufacturing procedures, improvement in the quality of printed components, and broadening the scope of printable materials and geometries.
Nevertheless, the execution of RAAM presents several difficulties. The customisation of collaborative robots, also called cobots, such as the UR3e model developed by Universal Robots, for additive manufacturing necessitates resolving several challenges. The factors mentioned above encompass the adaptation of the printing extruder, identification of appropriate materials, creation of sophisticated control software for converting 3D models into robotic commands, and meticulous calibration of the robot arm and extruder. A multidisciplinary approach is required for these areas, necessitating the integration of expertise from several fields, such as mechanical, electrical, automation, and software engineering.
The effective incorporation of RAAM technologies requires a deep understanding of robotic dynamics and additive manufacturing processes. This includes expertise in trajectory planning for robotic arms, optimal material extrusion, and balancing speed, precision, and material qualities.
The paper [3] plays a crucial role in this context, providing a novel perspective on controlling fibre orientation with a robotic manipulator and a multi-nozzle extrusion system. This approach significantly impacts the produced items' mechanical properties and surface finish, directly aligning with our focus on enhancing the quality and precision of 3D-printed components.
Further exploring the nuances of RAAM, paper [4] introduces a multitasking framework, spanning system design, integration, and generation of collision-free robot trajectories. Its use of closed-loop inverse kinematics to address challenges in redundant robots and the focus on robot tip orientation innovatively enhances the quality of manufactured surfaces. This methodology, validated through experimentation with a 7-axis redundant robotic manipulator, marks a significant stride in the field.
The paper [5] comprehensively reviews multi-DOF AM systems in another critical study. It underscores the evolution from traditional three-axis techniques to more complex multi-DOF configurations, enabling the production of intricately designed components. This review categorizes existing multi-DOF AM systems and offers insights into future research directions, contributing significantly to understanding AM technology evolution and its application in system design.
Complementing the diverse landscape of RAAM technologies, the comprehensive review [6] presents a broad spectrum of applications utilizing various industrial robots and materials. This review underscores the versatility and adaptability of robotic systems in additive manufacturing, ranging from 6-DOF ABB and UR3 robot arms to more complex 7-axis KUKA systems, each coupled with specialized extrusion heads. These systems handle various materials - from traditional clay and concrete to modern thermoplastics and composites - demonstrating the expansive potential of RAAM across different sectors. Projects like RoboFDM [7] with PLA and Large-Scale 3D Printing [8] with concrete illustrate the integration of robotic precision with material-specific requirements, paving the way for innovative solutions in manufacturing. This blend of robotic technology with various materials enriches the field of additive manufacturing and inspires novel approaches and potential applications in industries ranging from construction to intricate design fabrication.
Aligning with our research objectives, the study [9] delves into integrating additive manufacturing technology with robotics, focusing on the UR5 collaborative robot. This research highlights the simplification of robotic movements and the reduction of structural modifications in printing systems, mirroring our aim to enhance collaborative robots' adaptability in additive manufacturing. The methodologies and insights from [9] not only complement but also deepen our understanding of the complexities in merging these advanced technologies, guiding our advancements in RAAM.
These studies provide a rich tapestry of knowledge and innovation in RAAM. They highlight essential advancements, address critical challenges, and open pathways for future exploration, forming a comprehensive backdrop against which our research is positioned. This body of work informs our approach and underscores the dynamic and evolving nature of robotic-assisted additive manufacturing.
The structure of this paper is methodically organized as follows: The second section offers a detailed examination of the 3D printing process, encompassing an in-depth analysis of the employed techniques and materials. Subsequent to this, the third section delves into the pragmatic application of the UR3e collaborative robot within the additive manufacturing landscape. This portion meticulously documents the progression from the initial setup to the final execution of the process, accentuating both the encountered challenges and the strategies employed to

resolve them. Concluding the paper, the final section synthesizes the primary findings, sheds light on the broader implications of the research, and proposes directions for future exploration in this field. This segment serves as a reflective overview of the research contributions, underlining its importance within the evolving realm of robotic-assisted additive manufacturing. It aims to provide valuable perspectives on the wider impact of the study and potential advancements in this specialized area of technology.

2. MATERIALS AND METHODS

2.1. 3D Printing

The domain of 3D printing, a critical component of our research, has evolved into a highly competitive and demanding field, characterized by stringent requirements for dimensional accuracy, surface quality, and mechanical strength, all while aiming to reduce production time and costs. Amidst the advent of new technologies in this arena, the ability to meet elevated prototyping demands, particularly in terms of functionality, has significantly improved. However, achieving absolute control over these factors and attaining the desired level of perfection remains a substantial challenge, both for manufacturers and end users, when it comes to identifying optimal printing conditions that ensure repeatability and reliability.

A pivotal aspect in establishing these optimal conditions lies in the consideration of various influencing factors. These include, but are not limited to, the geometric specifications of the parts, the chemical composition of the filament material, the operational conditions of the printing machinery, post-printing positioning and fixing of the part, elements characteristic of specific 3D printing techniques, the configuration of the extruder assembly, and the printing parameters themselves.

For the experimental part of this research, the Fused Deposition Modeling (FDM) method was employed, as highlighted in Figure 1, [10]. FDM was selected due to its direct compatibility with the range of materials used and its adaptability to our specific robotic arm setup. In our setup, the FDM process involved using a direct drive printing head attached to the final element of the robotic arm, allowing for precise control over the material deposition. This method aligns with the current trends in the field which favor materials that facilitate optimal performance, especially for parts with complex surfaces. The extrusion challenges posed by these materials are effectively addressed by FDM, considering the geometry and dimensional characteristics of the part, thus avoiding the need for post-processing interventions. Achieving superior surface quality in our experiments was contingent on a detailed understanding and application of these optimal printing conditions.

Among several 3D printing methods currently in use – [11], such as Stereolithography (SLA), Selective Laser Sintering (SLS), Digital Light Processing (DLP), Multi Jet Fusion (MJF), PolyJet, Direct Metal Laser Sintering (DMLS), and Electron Beam Melting (EBM), FDM was deemed the most suitable for creating our proposed gripper solution due to its specific advantages.

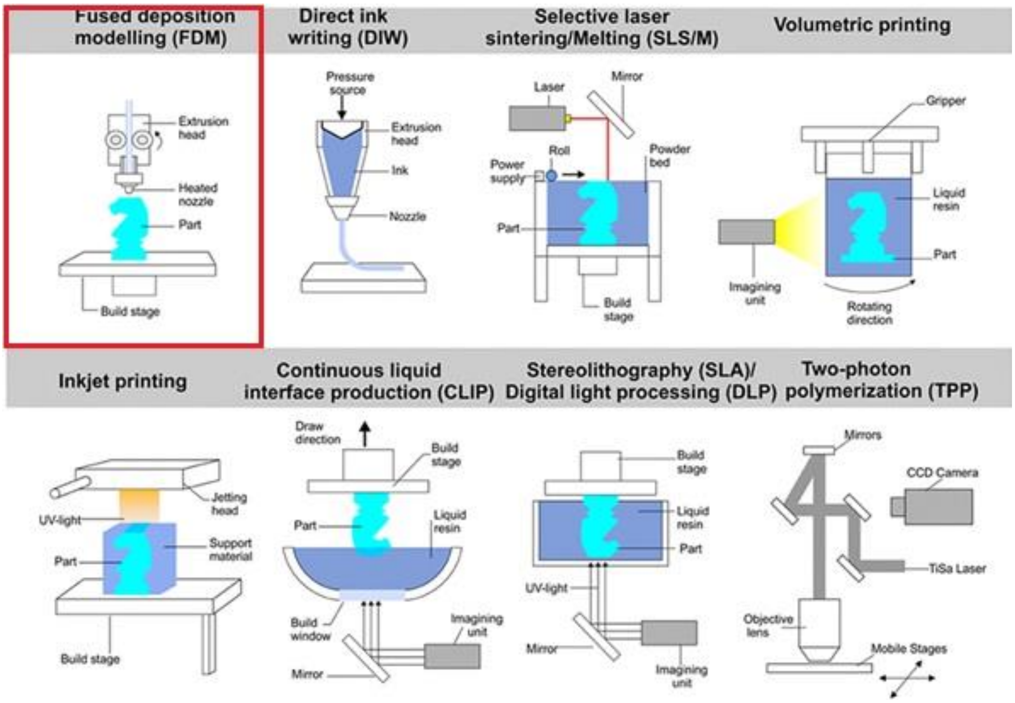

Fig. 1. Current technologies used in additive manufacturing [10]

2.2. Work methodology

To optimise the 3D printing process for our study, a methodology was developed to address the need for a definitive quantitative relationship between the constructive geometry, material type used, and their impact on the 3D printing process, as identified in the literature review. This gap necessitated an approach combining both experimental and analytical methods.

The methodology focuses on dynamically optimising the 3D printing process, considering key factors such as process productivity, surface quality, and production cost efficiency. The approach involved setting variable ranges for these optimisation factors while acknowledging the fundamental principle of the interdependent nature of these variables' actions.

The following objective functions guided the optimisation process:

- Productivity (P),
- Surface Quality (R),
- Production Costs (C).

To establish a quantitative understanding of how these objective functions relate to constructive geometry, the study identified and manipulated several critical optimisation factors, including:

- Nozzle Diameter (D),
- Extrusion Temperature (T),
- Step between Crossings/Routes (A),
- Material Deposition Rate (Q),
- Deposition Speed (V).

These factors were systematically varied in controlled experimental setups to observe and analyse their influence on the 3D printing process. The data gathered from these experiments was then used to establish a more concrete understanding of the interplay between these variables, aiming to optimise the process regarding productivity, surface quality, and cost-effectiveness. This methodology aimed to fill the knowledge gap identified in the literature and provide practical insights for improving the efficiency and quality of the 3D printing process.

The proposed objective functions, integral to our methodology, are conceptualised in the following form:

$$P=C_p e^{a1lgV} e^{a2Fp} e^{a3\alpha} e^{a4\lambda} e^{a5\delta HB}$$

$$R = C_R e^{c_1 \lg V_1} e^{c_2 F_P} e^{c_3\alpha} e^{c_4\lambda_R} e^{c_5\delta_{HB}}$$

$$C = C_C e^{b_1 \lg V} e^{b_{22} F_{Pz}} e^{b_3\alpha} e^{b_4\lambda} e^{b_5\delta_{HB}} \quad (1)$$

In the proposed objective functions, along with the previously mentioned notations, additional elements are considered:

Cp, C_c, C_R - constants

$a_i, b_i, c_i, d_i, f_i, g_i, h_i, m_i$ - the coefficients of the exponents (i=1...5),

These are considered linear functions of the five independent variables studied: Deposition Speed (V), Feed Rate (F), Specific Wavelength (λ_s), Density (ρ), and Heat Dissipation (dH).

In relation (2), the coefficients of a_i .. c_i (i=0_5) are considered constants, which limits from the beginning the degree of approximation of the Y_i functions.

$$Y_1 = a_0 + \sum_{i=1}^{i=5} a_i x_i$$

$$Y_2 = b_0 + \sum_{i=1}^{i=5} b_i x_i$$

$$Y_3 = c_0 + \sum_{i=1}^{i=5} c_i x_i \quad (2)$$

The constancy assumption for these coefficients simplifies the models but also confines the scope of their predictive accuracy. By fixing these coefficients, the models primarily focus on understanding the linear relationships and direct impacts of the independent variables on the objective functions without delving into more complex, non-linear interdependencies that might exist.

To ascertain the coefficients in relations (2), the technique of experimental design [12-13] will be employed, offering distinct advantages over alternative experimental methods, such as:

- Minimal number of required experiments;
- Enhanced precision of the derived mathematical model;
- Uniform and equal distribution of experiments across the entire defined domain, ensuring the objective function is valid throughout the area of study.

Due to the inability to describe the range of variation of independent variables in relations using linear approximation, particularly because interaction effects are not highlighted, a second-order compound experimental plan will be utilized [14]. The implementation of this plan involves steps depicted in Figure 2.

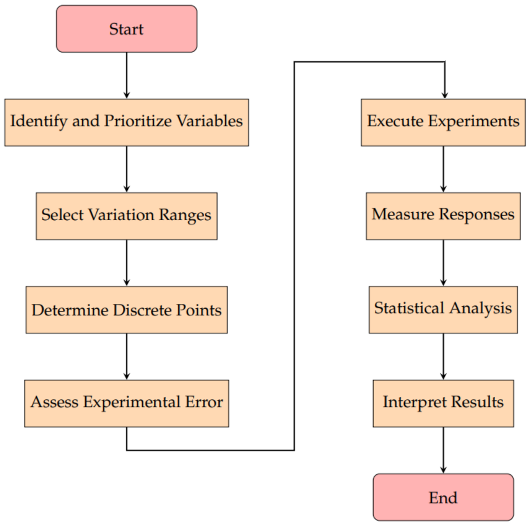

Fig. 2. The diagram of experimental methodology for dynamic optimization in 3D Printing

3. RESULTS AND DISCUSSIONS

The project's workflow encompasses a progression from CAD conceptualization to the refinement of the 3D printed artefact with the integration of a robotic arm, delineated in Figure 3. This representation elucidates the sequence of operations to transform a digital model into its physical counterpart.

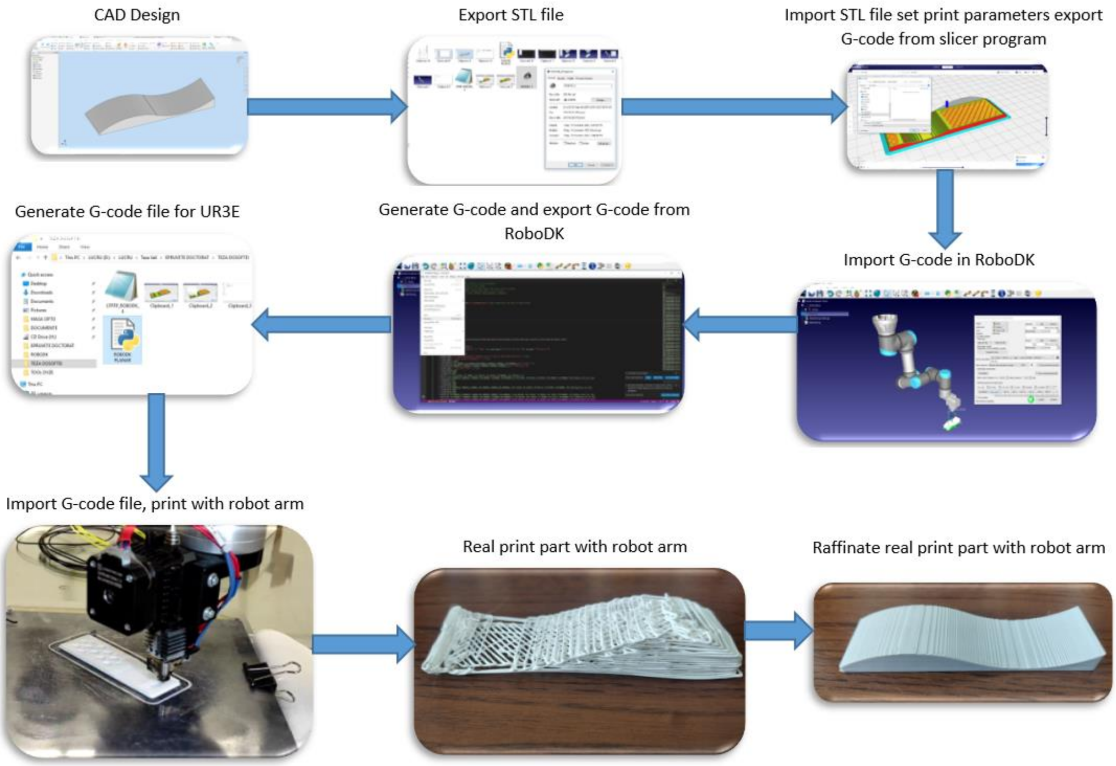

Fig. 3. – The workflow implemented in project

After the initial CAD design phase, the process advances to importing the STL file into a slicing software, exemplified by the CURA program. This stage is critical for establishing the precise printing parameters governing the subsequent fabrication process. Key parameters configured at this juncture include selecting the material type, setting the printing temperature, determining printing speed, layer height specification, infill percentage, and the bed temperature to ensure optimal adhesion. Each parameter is meticulously adjusted to align with the specific requirements of the printed object, thereby optimizing the conditions for a successful print. This careful calibration of settings is crucial in ensuring the fidelity of the printed thing to its digital counterpart, impacting both its structural integrity and surface quality.

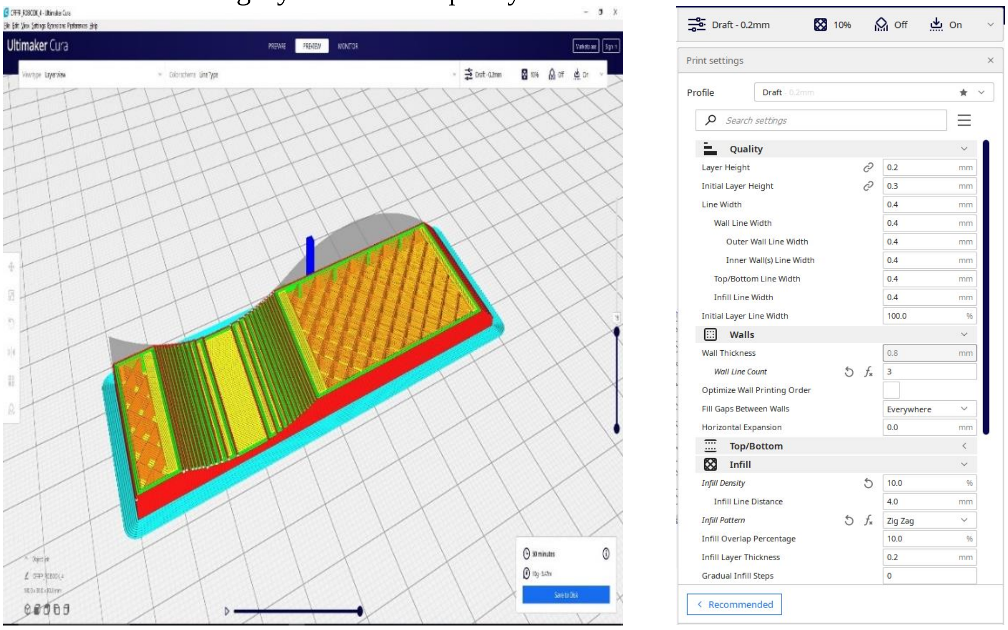

Fig. 4. Importing STL file into CURA software and setting print parameters

The calibration of print settings, a critical determinant for achieving optimal print quality and structural integrity, is elucidated in Figure 4. This figure delineates the intricate process of importing an STL file into a slicing application, exemplified by CURA, followed by adjusting various print parameters. It comprehensively depicts the software interface, detailing the array of customizable options, including material selection, temperature configurations, printing velocity, layer thickness, infill density, and heated bed temperature. Figure 4 exemplifies the preparatory phases of transitioning from a digital design blueprint to the tangible printing process, underscoring the complexities and essential considerations requisite for efficacious 3D printing.

After the parameterization of the printing process and the exportation of the G-code delineating print head trajectories, attention is directed towards the virtual construction of the workstation, a pivotal stage where the RoboDK software assumes a central role. At this stage, the workstation is virtually assembled within RoboDK, incorporating the importation of a UR3E robot from Universal Robots and integrating a print head from DYZE DESIGN into the simulated environment.

RoboDK software is indispensable in this workflow because it facilitates offline programming and motion simulation across a diverse spectrum of industrial and collaborative robotic platforms. It significantly optimizes the virtual simulation procedure, thereby augmenting efficiency and accessibility throughout the various stages of the project. Furthermore, the software's adaptability in accommodating an array of robotic configurations obviates the necessity for proficiency in diverse, proprietary programming languages and environments.

The project substantially benefits from the streamlined programming processes and the versatility proffered by RoboDK, rendering it an essential instrument in establishing the virtual workstation. To visually manifest this facet, Figure 5 is presented, showcasing both the virtual model of the robot as conceived in RoboDK and its physical analogue. A salient feature illustrated in this figure is the strategic mounting of the real robot model on the ceiling of a frame composed of aluminium profiles. This portrayal accentuates the precision and authenticity achieved in the virtual simulation and exhibits the meticulous replication of actual operational conditions within the RoboDK environment. Consequently, it exemplifies the software's proficiency in bridging the gap between virtual planning and real-world execution, a quintessential attribute of modern robotic-assisted additive manufacturing.

In the subsequent phase, the G-code program generated by the CURA software was imported into the RoboDK environment. This was essential for aligning the detailed printing parameters with the robotic functionalities.

Within RoboDK, specific printing speeds suitable for the UR3E robot were chosen, ensuring synchronization between robotic movements and printing requirements. Following this, the G-code was generated within ROBODK, involving a detailed visualization and optimization of the printing trajectory as determined by the robotic arm's path.

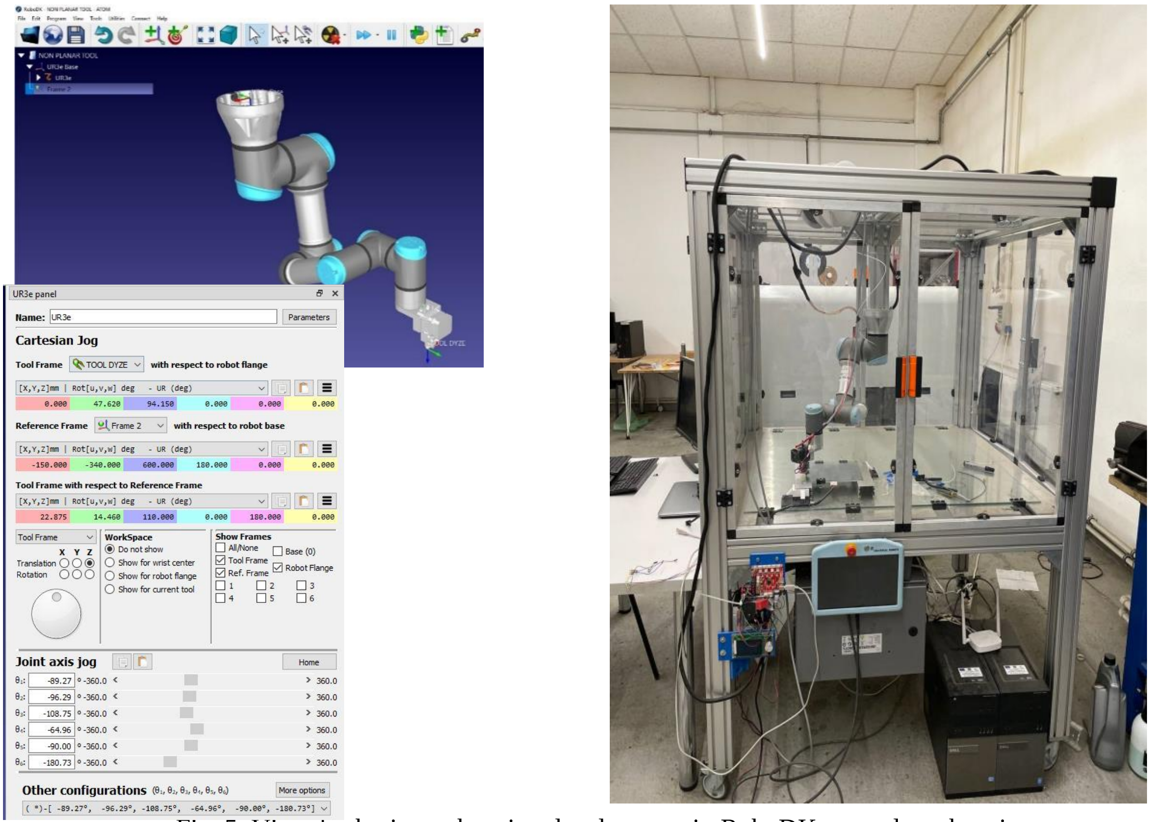

Fig. 5. Virtual robotic workstation development in RoboDK vs. real workstation

This process allowed for necessary adjustments before finalizing the code, ensuring accuracy and precision in the print job. The visualization within RoboDK not only guaranteed the accuracy of the print job but also enabled a thorough review and optimization of the robotic arm's movements for efficient and precise 3D printing. Finally, the G-code was exported from RoboDK – Figure 6, translating detailed instructions into a format compatible with the robot's control unit, marking a critical juncture in the transition from virtual simulation to physical realization.

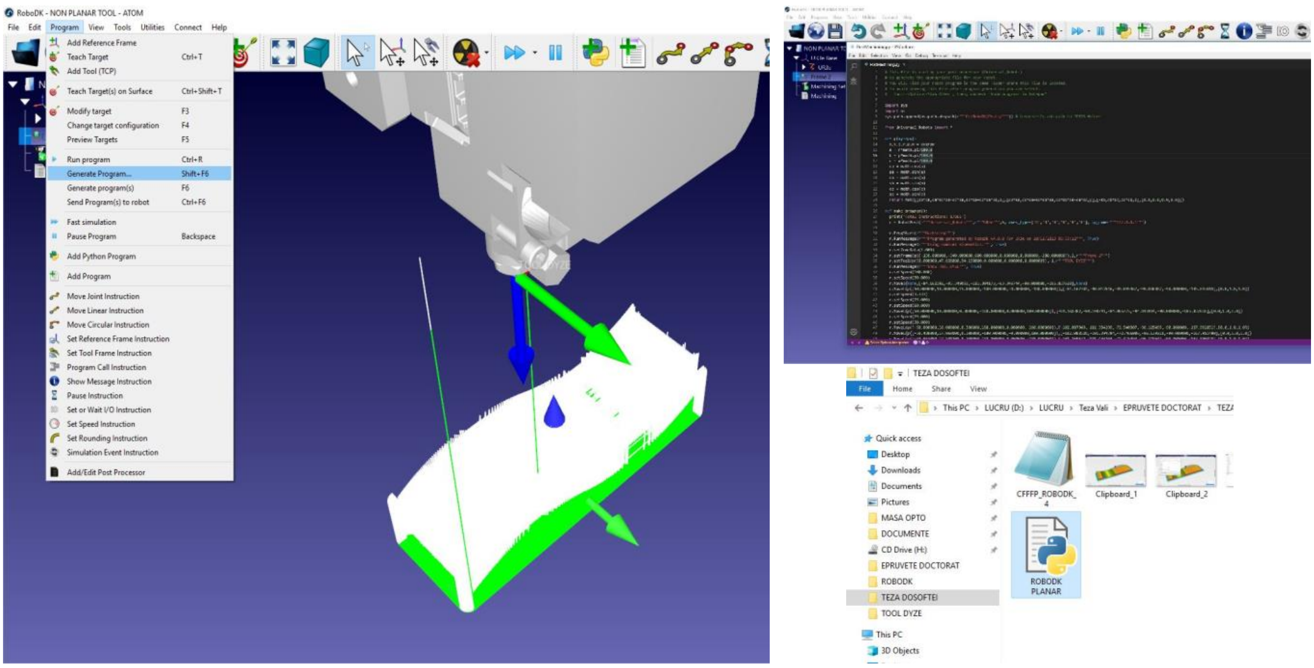

Fig. 6. Exporting G-code program from RoboDK for the UR3e cobot

The successful outcome of the 3D printing process with the UR3e cobot is exemplified in Figure 7, which presents a sample piece indicative of the capabilities of this technology.

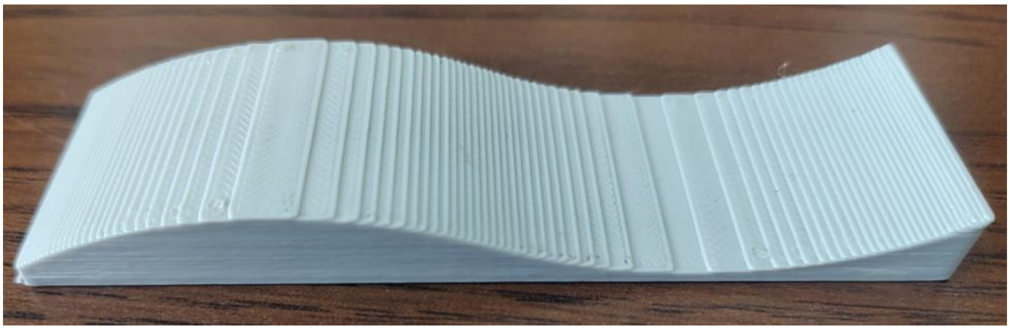

Fig. 7. Sample printed piece by UR3e robot'

This sample was executed with the print parameters finely tuned to a nozzle temperature of 235 degrees Celsius, layer height of 0.2mm, printing speed of 40mm/sec, and a heated bed at 70 degrees Celsius, and the resultant piece showcases the intricate detail and structural integrity that can be achieved. It represents the technical feasibility of using the UR3e cobot for additive manufacturing tasks and highlights its proficiency in delivering consistent and high-fidelity results.

4. CONCLUSIONS

The research delineated in this paper contributes to the discourse of Industry 4.0, particularly emphasising the synergistic integration of additive manufacturing and advanced robotics within the manufacturing sector. This integration, exemplified through 3D printing and the UR3e cobot, marks a significant stride towards realising intelligent manufacturing systems. It indicates a paradigmatic shift towards enhanced efficiency, flexibility, and a redefinition of traditional manufacturing boundaries.
The advancement in additive manufacturing, especially evident through the systematic application of 3D printing, has revolutionised conventional manufacturing frameworks. This technological leap has facilitated increased design flexibility and material efficiency and enabled the production of complex geometries more economically. The implications of this shift are far-reaching, extending beyond industrial processes to challenge and redefine existing supply chain models and product life cycles.
In the sphere of RAAM, integrating the UR3e collaborative robot illustrates the potential of combining robotic precision with the innovative capabilities of 3D printing. This research demonstrates the practical viability of RAAM and its substantial potential in refining manufacturing processes. However, deploying RAAM necessitates addressing several complex challenges, including customising cobots for additive manufacturing tasks. This requires a multidisciplinary approach, amalgamating mechanical, electrical, automation, and software engineering knowledge.
The current investigation represents an intermediary phase in the authors' broader project trajectory. The ultimate aim is to explore the feasibility and advantages of non-planar printing using industrial robots, motivated by the prospect of achieving enhanced structural strength and durability in printed objects. This future direction aims to transcend the existing limitations of additive manufacturing, exploring new frontiers in materials, print quality, and application scopes.

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