Closing the Gap: Exploring Approaches for Printing Lightweight Curved Pipes with Carbon Fiber Reinforced Thermoplastics

Zsolt Kállai[1], Johann Kipping[1] and Thorsten Schüppstuhl[1]

[1] Institute of Aircraft Production Technology, Hamburg University of Technology, Hamburg, Germany
Email: zsolt.kallai@tuhh.de, Web Page: https://www.tuhh.de/ifpt/

Keywords: Continuous Carbon Fiber, 3D Printing, Curved Pipes

Abstract

This paper explores the innovative integration of Carbon Fiber Reinforced Polymers (CFRP) and Fused Filament Fabrication (FFF) technology to enable the on-demand printing of complex curved pipes. Traditional methods for manufacturing curved pipes face challenges in complexity and cost, prompting the need for advanced additive manufacturing techniques. This study presents two novel methods: the cut-and-place method and the compensating matrix layer method, to address the challenge of creating non-uniform layer heights with CFRP in 3D printing. These methods involve stacking segments of CFRP or adding compensating matrix layers to achieve efficient fabrication of curved pipes. The research outlines the materials considered, including continuous CFRP filament and matrix filament, and discusses challenges such as layer height control and minimum placeable length of the CFRP material. The findings aim to advance additive manufacturing techniques and facilitate the production of lightweight, individualized curved pipes for various industrial applications.

1. Introduction

In manufacturing, there is a continuous search for components that are both lightweight and strong. This stems from the demand for efficiency, particularly in industries like aerospace, automotive, and others, where reducing weight can improve performance and save costs. Carbon Fiber Reinforced Polymers (CFRP) have emerged as a promising solution, offering the desired combination of strength and lightness, particularly in the form of thin-walled components. Additive manufacturing (AM) has revolutionized traditional manufacturing methods by enabling on-demand production, design flexibility, and cost-effective fabrication of small batches. Among various AM techniques, Fused Filament Fabrication (FFF) stands out for its simplicity, material compatibility, and ease of use. By precisely placing single strands of fiber and constructing thin-walled structures, FFF holds the potential to leverage the benefits of CFRP in a cost-effective and efficient manner. One application where the advantages of CFRP and FFF converge is in printing curved pipes. This application field often necessitates individual and lightweight components that can be replaced on-demand, making them an ideal candidate for additive manufacturing. However, traditional FFF methods face challenges in printing non-planar parts and ensuring optimal load orientation, particularly when working with CFRP. While CFRP with FFF holds potential, its application in parts such as curved pipes is still in its developmental stage. This creates the need for innovative methods to address current limitations and harness the full potential of this technology. Therefore, the primary objective of this research is to present viable approaches to overcome the challenges, enabling the on-demand printing of complex and highly individual curved pipes with CFRP using FFF. By doing so, this work aims to contribute to the advancement of additive manufacturing techniques and facilitate the widespread adoption of CFRP in diverse industrial applications.

2. State of the Art

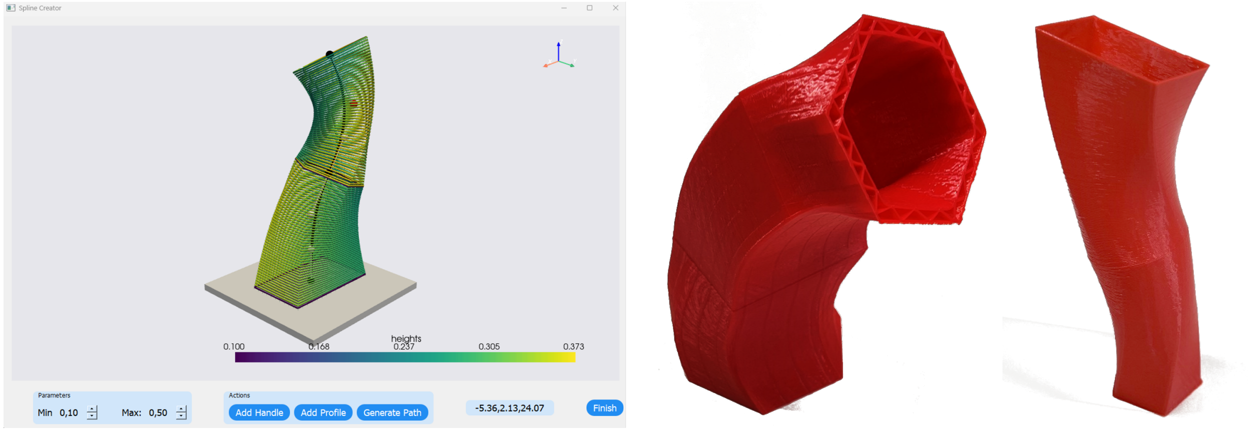
Pipe manufacturing processes for CFRP, such as winding, braiding, pultrusion, and roll wrapping, are established and produce parts of high quality. However, these methods encounter limitations when dealing with curvature. Notable solutions include bending as a post-processing step or utilizing non-concentric mandrels to facilitate the creation of curved pipes. Companies like Alforment [1] and Ollow [2] have explored innovative approaches like this to address the challenge of manufacturing curved pipes. While these methods expand the possibilities, they still face constraints. The dependency on mandrels restrict the feasible curvature and more complex shapes often include labor-intensive hand lamination. The joining of components presents another hurdle, where conventional methods such as gluing, riveting, or drilling and fastening introduce weaknesses at joint areas, potentially compromising structural integrity and durability.

3D printing technologies offer a solution for overcoming existing limitations in the form of printable forms. This enables the cost effective manufacturing of small batch parts. This method however is still dependent on manual labor and the printed form typically becomes obsolete after a single use, which represents material waste.

If the curved CFRP pipes could directly be printed with FFF, the advantages of FFF and the composite material could be combined with minimal material waste. In the following, the existing approaches for printing curved pipes with FFF are presented. To the knowledge of the authors the printing of freeform curved pipes with only CFRP has not been realized yet. The reasons for this and the most significant challenges are presented in the subsequent section 3. An approach by Zhang et. al. tries to circumvent these challenges, by choosing a hybrid approach where the a core is printed with conventional FFF and CFRP is printed on this hollow form [3]. A benefit of this approach is that the fibers can be placed in radial or axial direction. Their method is limited to parts with biaxially symmetric cross sections and requires the printing of a core from a neat polymer which represents ineffective material usage. In [4] Berndt et. al. implemented an equivalent to filament winding with additive manufacturing with a 4th axis on a Markforged [5] printer. The process exhibits similar limitations as the classical filament winding method, requiring a mandrel and being restricted in the manufacturable geometries.

Existing approaches of printing pipes or other thin walled structures with FFF oftentimes facilitate multi-axis printers, which employ two or more additional axes to enable to change the angle of nozzle and print bed during the printing process. This multi-axis approach offers the possibility of printing in non-planar layers or multi-planar form, where the layers are planar but oriented. For manufacturing thin-walled structures helical slicing or approaches like vase-mode are often employed. A typical approach to non-planar slicing which can also be applied to pipes is isothermal surface slicing. Shan et. al. present a method where a tube is printed on a water soluble core to demonstrate this method [6]. Li et. al. print thin walled parts by a non-planar approach with a robot to avoid support structures [7]. A screw extruder is used for fast material deposition. Zhang et. al. investigated the reinforcement in the z-direction of pipes due to weak layer adhesion in [8] before applying it to CFRP in [3]. A challenge in path planning are bifurcating forms or branching structures. Mitropoulou et. al. solve this by constructing a reeb graph from the input which then allows for a decomposition to be computed [9]. In [10] Gunipar et. al. present a helical slicing method, where tool collisions are avoided and paths are created using a probabilistic roadmap algorithm. This method, like other helical slicing variants, shows potential for the printing of pipes. To be able to follow a lead line with the orientations of the layers in which the pipe is printed, the amount of extruded material is varied dynamically, which in turn results in locally varying layer heights. By aligning the layer direction with the orientation of the pipe, the weaker interlaminar adhesion always points along the pipe making the parts strength more homogeneously distributed and increasing strength in the radial direction. Furthermore, no supports are needed as material is always deposited onto existing part structures.

In the research project supporting this publication, the authors have developed a path planning software for printing arbitrary pipes on the printing system described in section 4. An example for a planned path and printed part can be seen in Figure 1. The pipe is defined by user-given supporting points that are interpolated



Min 0,10 Max: 0,50

-5.36,2.13,24.07

Figure 1: Left: Pipe path planner with user interface displaying an example path of a curved pipe. Right: Printed thermoplastic exemplary curved parts with and without infill.

to a lead line, around which a profile is swept and morphed between the points. The developed algorithm allows for arbitrary cross sections and also supports non-planar printing. This allows any surface to be used as a base layer, enabling pipes to be printed on existing parts by first scanning the surface and adaptively slicing the part before placing the initial layer.

3. Materials and Challenges

This section aims to describe the materials considered in this work and presents the challenges at hand. In this paper, the term ‘filament’ is used exclusively in the context of 3D printing, where it denotes the print material, and should not be confused with its meaning in the composite sense, where it refers to the individual fiber.

3.1. Materials

The methods presented in this study require the use of a continuous CFRP filament and a matrix filament corresponding to the matrix material of the CFRP. The application of the matrix material is essential due to the challenges involved in placing the CFRP material, a topic detailed extensively in this chapter.

The primary material is a pre-impregnated, continuous carbon fiber reinforced thermoplastic, while the second material is a pure thermoplastic filament. The matrix material is used to fill the gaps, regions where continuous fiber placement is unfeasible, ensuring the creation of complete parts. This material was chosen based on its compatibility with CFRP and is expected to provide excellent adhesion between the materials.

Moreover, there is potential for substituting the matrix material with chopped fiber reinforced matrix material to further enhance the mechanical properties of the resulting printed part. However, it is essential to note that due to the abrasive nature of the chopped fibers, the printing hardware that comes in contact with this material must be regularly inspected for signs of wear that could alter the quality of the finished products. This consideration is equally applicable to the CFRP material.

3.2. Challenges

In contrast to 3D printing with conventional thermoplastic materials, where the amount of extruded material can be varied to create non-uniform layer heights, the utilization of CFRP material poses additional challenges. These challenges must be addressed to successfully print curved carbon fiber pipes.

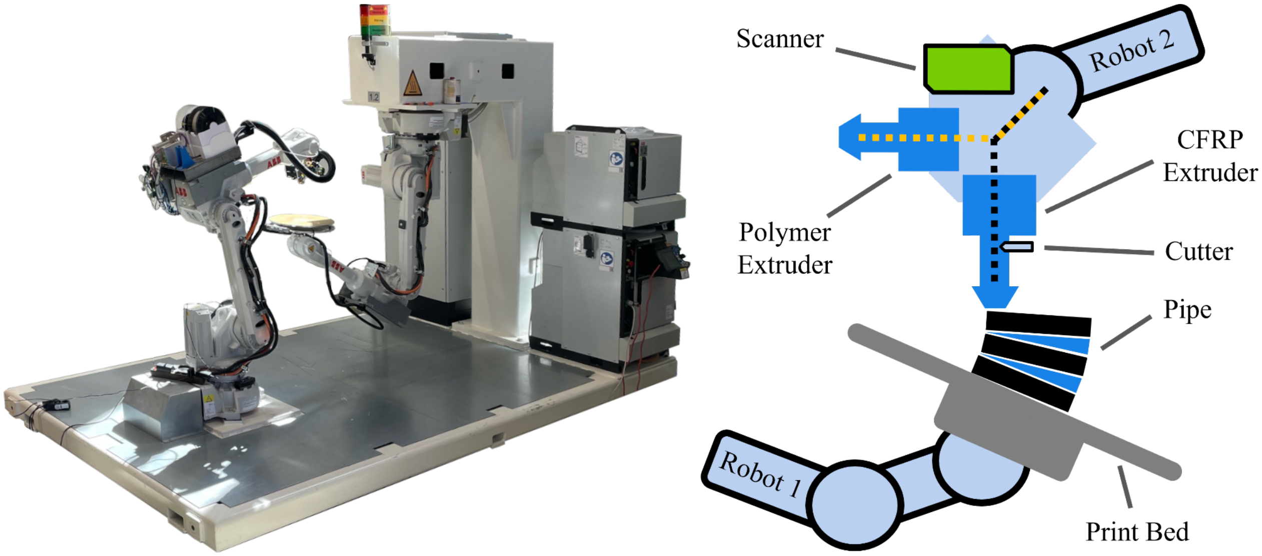


Figure 2: Left: 12-Axis printing system using two robots. Right: Print head with labeled components.

3.2.1. Layer Height

One such challenge is the inability to modify the layer height of the printed part, as it is predetermined by the fixed fiber to matrix ratio of the filament. Decreasing the layer height results in fiber compaction, exerting force that can damage or break the fibers within the placed material. Conversely, increasing the distance to the previous layer leads to inadequate compaction between layers in the build direction that negatively effects the quality of the finished part. As the layer height of the CFRP material is not modifiable, the matrix material is chosen to enable the fabrication of layers with non-uniform layer heights.

3.2.2. Minimum Placeable Length of the CFRP Filament

Another challenge in the printing process is the minimum placeable length (MPL) of the CFRP material. This parameter determines the length of the shortest segment of the primary material that can be placed. When segments shorter than the MPL are required, they must be filled with the matrix material. The parameter depends on the physical dimensions of the print head, particularly the distance between the nozzle's outlet and the cutting mechanism. In CFRP 3D printers, where cutting occurs automatically, the cutter is positioned between the extruder and the nozzle. Consequently, once the cutting process is completed, the material between the cutter and the nozzle's outlet cannot be moved by the extruder. Therefore, to remove this material segment, it must be pushed or pulled out. Pushing out the remaining material with new filament can lead to filament breakage and subsequent clogging of the filament guiding tube. A pragmatic solution to this challenge is to remove the residual material by continuing the printing process.

4. Hardware

In order to manufacture the pipes with the proposed methods, a printing system is required. The machine used by the authors is a 12-axis, dual robot system presented in [11], which can be seen in Figure 2. Non-planar printing is already possible with classical 3-axis systems, but this multi-axis research system enables printing in arbitrary orientations, switching print heads with a rotating head and has a higher degree of flexibility, making it well suited for research. The two manipulators are synchronized and a line-scanner allows for printing on existing non-planar surfaces as mentioned at the end of section 2.

The CRFP print head is mounted in a rotatable configuration with a neat polymer extrusion system, so a material change can be done by simply rotating the last axis of the upright robot. The print bed is fixed to

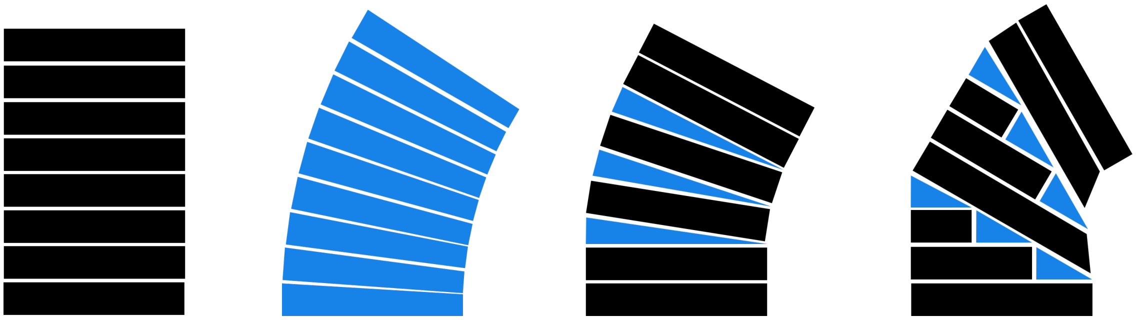


Figure 3: CFRP in black, polymer in blue. Left to right: Pure CFRP straight section. Pure polymer curved pipe; local layer height variation required. Visualization of the compensating matrix layer method. Visualization of the cut-and-place procedure.

the other robot, that is mounted in the overhead position. One important component in the print head is the cutting unit that is realized with a pneumatically actuated industrial knife.

5. Methods

Two methods are proposed in this work for the 3D printing of curved carbon fiber tubes using primarily the CFRP material and a multi-material printing system. In both methods, the pipes are segmented into straight and curved sections. The straight sections are printed exclusively with the primary material, while the curved sections are printed alternately with the CFRP and the matrix materials. To ensure the successful fabrication of curved carbon fiber pipes, it is crucial to create layers with non-uniform layer height. This can be accomplished by either stacking segments of deposited material or employing the matrix material to compensate for the difference in height between the fixed CFRP layer and the required non-uniform layer. In both approaches, any gaps or missing segments must be filled with the secondary material to ensure a proper part.

5.1. Cut-and-place Method

The first method utilizes a cut-and-place procedure to generate the non-uniform layers of the curved sections of the pipe. This is achieved by stacking multiple segments of CFRP, each varying in length, created by cutting the primary material. The slicing calculations for this procedure are determined by the MPL and the fixed layer height of the CFRP material that is specified by the filament's manufacturer. The objective of this approach is to maximize the fiber volume fraction of the printed part.

To generate a non-uniform layer, it is initially divided into sublayers. The first sublayer, printed exclusively with the reinforced material, forms a closed profile atop the preceding layer. The following sublayers of CFRP material are then stacked in a stair-like fashion to approximate the desired layer, as shown in Figure 3. To complete the non-uniform layer, the matrix material is applied to fill the areas where the primary material could not be placed.

The process continues with subsequent non-uniform layers until the curvature is complete. Once the curvature is printed, the next section is fabricated. If a straight section follows, printing is exclusively performed with the CFRP material. Conversely, if another bend comes next, the cut-and-place process is repeated until the part is fully fabricated.

5.2. Compensating Matrix Layer Method

The second approach involves creating non-uniform layers by adding a partial compensating matrix layer on top of the CFRP layer. This matrix layer compensates for the varying distances between two CFRP layers in the curved sections of the pipe. Similar to the cut-and-place process, the creation of non-uniform layers occurs step by step.

Initially, the CFRP layer is placed. Once this step is completed, the remaining area between the required non-uniform layer and the placed CFRP layer is filled with the matrix material, as depicted in Figure 3. To ensure a high fiber volume fraction in the printed part, the matrix layer must be minimized, which may involve eliminating the distance between sections of two CFRP layers whenever possible, depending on the curvature.

The process proceeds with printing the next CFRP layer, which is again compensated by the required amount of matrix material. This alternating pattern between the two materials persists until the bend is fully printed. Subsequently, if a straight section follows, only the primary material is utilized to complete this segment. However, if another bend follows, the compensating matrix layer method is once again employed in the subsequent curvature. These processes are repeated until the curved carbon fiber pipe is completed.

6. Discussion and Outlook

The cut-and-place and compensating matrix layer methods aim to provide solutions for creating layers with non-uniform layer height using the CFRP material for 3D printing carbon fiber reinforced curved pipes. These methods involve stacking segments of the primary material or adding minimal compensating layers between CFRP layers to manufacture pipes in a novel and efficient manner compared to conventional processes. Leveraging the advantages of 3D printing, these methods could enable the creation of pipes with various curvatures, profiles, and sizes without the need for manual labor or molds. Furthermore, successful implementation of these approaches could open up possibilities for fabricating complex structures such as branching pipes or integral parts like pipes with printed-on fixation points.

While the presented methods offer innovative solutions for creating curved CFRP pipes, they also introduce significant challenges that have to be addressed. One limitation concerns the fiber volume fraction of the printed parts, which is highly dependent on the fiber volume fraction of the CFRP filament. Moreover, as the matrix material is additional used in the curvature, the fiber fraction in the printed part is further reduced. Consequently, the finished parts may not meet the requirements for high-performance applications, which often demand higher fiber volume fractions to achieve optimal strength and stiffness. Furthermore, the material changes required for creating non-uniform layers could be time-intensive, during which the placed material may cool, potentially hindering proper adhesion of the subsequent layer. This could lead to structural weakness in the finished part that is likely to fail in the curved section. While printing CFRP segments on the curvature for local strengthening could increase strength, the placement of these would require complex material placement based on the actual scan of the printed part. Moreover, to enhance layer adhesion, an additional heat source could be applied to enable better bonding.

Beyond material issues, the printing hardware also poses challenges. While the robot-based setup allows for high flexibility and support-free printing, the absolute accuracy of the robots could be a limiting factor in fabricating curved pipes. As material placement requires precision and the axis configuration could change during the material change procedure, the paths of the robots might need recompensation. This could be addressed by utilizing a scanner, as mentioned previously, but scanning each layer after placement would significantly increase printing time. Alternatively, the issue could be tackled by enhancing the accuracy of the robot-based hardware, either through an external visual system that precisely tracks the robots' position or through additional external encoders to provide better position control.

It is also important to note that while the presented methods are applicable with pre-impregnated filament, there may be alternative FFF-based solutions that could create non-uniform CFRP layers. In-situ fiber impregnation and coextrusion techniques both have the potential to influence the amount of placed matrix material during deposition, by varying the speed of material feed for the matrix. However, these approaches have not yet been thoroughly tested and validated for creating curved CFRP pipes, which should be investigated in future works.

The next step involves implementing both methods and conducting thorough testing on the experimental setup to determine their limitations concerning feasible curvatures and the size and shape of applicable profiles. It is essential to note that in certain configurations, it may be necessary to employ both methods within the same curvature to maximize the fiber volume fraction of the part.

Subsequently, a material study must be conducted to evaluate the adhesion between the primary and the secondary materials. This study aims to provide insights for further refining the introduced approaches to create parts without lamination defects. Additionally, the printability of the matrix material needs to be investigated, with a focus on determining the smallest feasible layer height and evaluating the effectiveness of gap filling after the CFRP material placement. Regarding the former, material tests with the experimental setup are necessary to define the minimum layer height that is feasible with the robot-based setup. The effectiveness of gap filling needs to be investigated, where the material flow must be precisely synchronized with the robot's position. Unoptimized material flow could result in the placement of additional material where it is not intended or leave gaps within the placed profile, potentially causing insufficient layer adhesion for subsequent layers.

In addition to implementing and testing the methods, further improvements could be made to the cutting mechanism to reduce the MPL. If the cutting procedure could be positioned closer to the nozzle's outlet, potentially even at the tip of the nozzle without impeding the printing process, smaller segments of CFRP material could be placed. As a result, the use of the matrix material could be further minimized, leading to an increased fiber volume fraction in the finished parts.

The proposed methods offer a promising approach for creating non-uniform CFRP layers with a multi-axis, multi-material printing system, thereby advancing the field of research and establishing 3D printing as a viable process for fabricating curved carbon fiber pipes.

Acknowledgments: This research was funded by the Federal Ministry for Economic Affairs and Climate Action of Germany (BMWK), through the Federal Aviation Research Programme (LuFo VI-2).

References

[1] Alformet. https://www.alformet.com. 2020. [Online]. Available: `https://www.alformet.com` (visited on 08/05/2024).

[2] Ollow. 2018. [Online]. Available: `https://www.ollow-tech.com/en/` (visited on 08/05/2024).

[3] H. Zhang, X. Lei, Q. Hu *et al.* Hybrid printing method of polymer and continuous fiber-reinforced thermoplastic composites (cfrtpcs) for pipes through double-nozzle five-axis printer. *Polymers*. Vol. 14. No. 4. 2022. ISSN: 2073-4360. DOI: `10.3390/polym14040819`.

[4] A. Berndt, M. Laux, H. Oberlercher, R. Heim and F. Riemelmoser. Additive manufacturing of continuous carbon fiber tubes and experimental investigation of the energy absorption capability under quasi-static loading. *Procedia Structural Integrity*. Vol. 34, pp. 105–110. 2021. The second European Conference on the Structural Integrity of Additively Manufactured Materials. ISSN: 2452-3216. DOI: `https://doi.org/10.1016/j.prostr.2021.12.016`.

[5] Markforged. 2014. [Online]. Available: `https://markforged.com` (visited on 08/05/2024).

[6] Y. Shan, Y. Shui, J. Hua and H. Mao. Additive manufacturing of non-planar layers using isothermal surface slicing. *Journal of Manufacturing Processes*. Vol. 86, pp. 326–335. 2023. ISSN: 1526-6125. DOI: `https://doi.org/10.1016/j.jmapro.2022.12.054`.

[7] X. Li, W. Liu, Z. Hu *et al.* Supportless 3d-printing of non-planar thin-walled structures with the multi-axis screw-extrusion additive manufacturing system. *Materials Design*. Vol. 240, p. 112 860. 2024. ISSN: 0264-1275. DOI: `https://doi.org/10.1016/j.matdes.2024.112860`.

[8] H. Zhang, W. Zhong, Q. Hu, M. Aburaia, J. Gonzalez-Gutierrez and H. Lammer. *Research and implementation of axial 3d printing method for pla pipes*. 2020. DOI: `10.3390/app10134680`.

[9] I. Mitropoulou, M. Bernhard and B. Dillenburger. Nonplanar 3d printing of bifurcating forms. *3D Printing and Additive Manufacturing*. Vol. 9. No. 3, pp. 189–202. 2022. DOI: `10.1089/3dp.2021.0023`.

[10] E. Gunpinar and A. Armanfar. Helical5am: Five-axis parametrized helical additive manufacturing. *Journal of Materials Processing Technology*. Vol. 304, p. 117 565. 2022. ISSN: 0924-0136. DOI: `10.1016/j.jmatprotec.2022.117565`.

[11] Z. Kallai, M. Dammann and T. Schueppstuhl. Operation and experimental evaluation of a 12-axis robot-based setup used for 3d-printing. In *ISR 2020; 52th International Symposium on Robotics*. 2020, pp. 1–9.