Cartesian models can be obtained. This is an optional step for better visualization, as the main purpose of the methodology is to obtain RBNPAM trajectories for a robot-based multi-material MEX station. The Cartesian models are shown in Fig. 7.13.

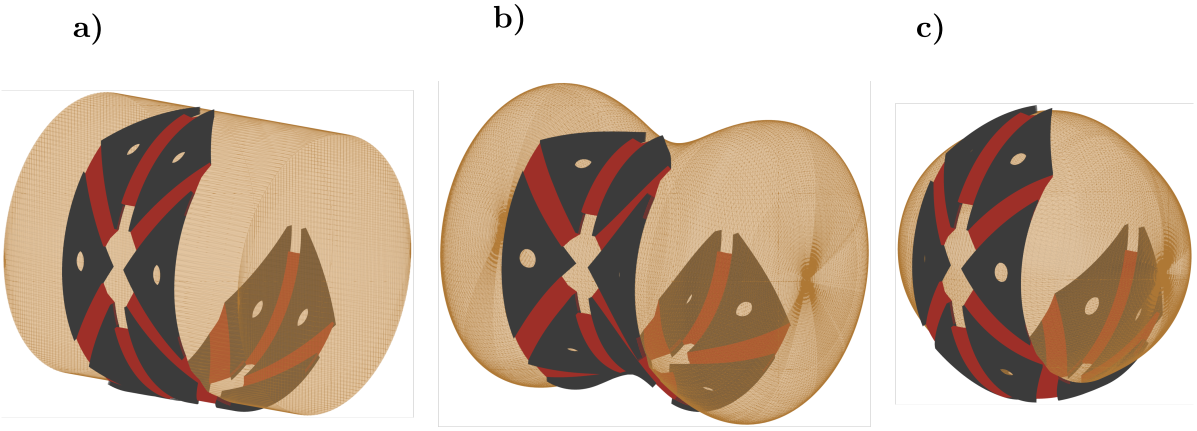

Figure 7.13: Cartesian models located on their build platforms. a) Cylinder case. b) Double curvature case. c) Hollow case.

Regarding the trajectory generation, Fig. 7.14 shows the trajectory generated by the commercial software CURA when the scaled model is sliced. After this process is done, the resulting code is parsed, but not interpolated, since the θ resolution was considered sufficient for the purposes of this work. This process is done for the three selected build platforms. The result for the double curvature case is shown in Fig. 7.15. Only the trajectories of the first layer are shown to simplify the image.

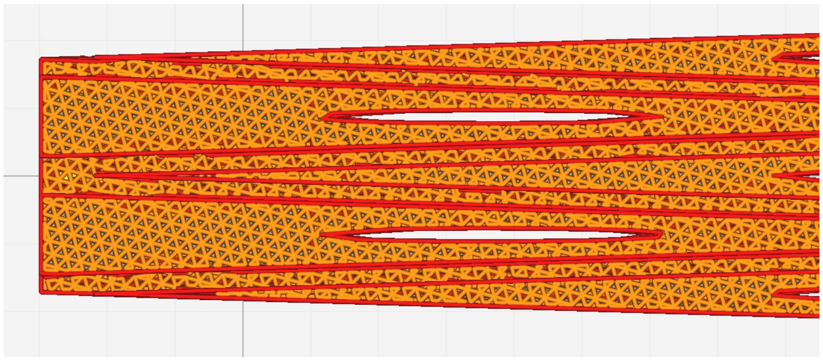

Figure 7.14: Detail of cross-section of planar toolpaths made by Ultimaker Cura. Shell trajectories in red, infill (100%) trajectories in orange.

It can be observed that the travel paths cross the print bed since this software is not adapted for non-planar trajectories. Ensuring the correct functioning of travel paths, along with the flexibility to infill using different densities in the $L\theta-$plane, was the main reason for developing a custom slicer.

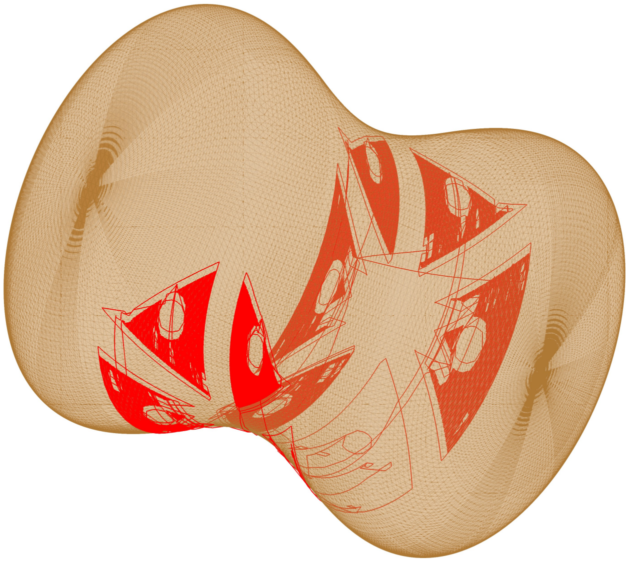

Figure 7.15: RBNPAM trajectory (red line) for the double curvature case (build platform in yellow). Only the first 250000 points are represented for clarity.

7.3 Texture mapping

7.3.1 Case study description

This case study investigates the integration of Non-Planar Additive Manufacturing (NPAM) technology with robotic systems to map complex textures onto curved surfaces. The proposed methodology leverages trajectories generated by a topology-based algorithm that employs subspace transformations to define texturization patterns on intricate geometries. This approach ensures the uniform application of textures, maintaining a consistent density even on surfaces with variable curvature.

Surface texturization plays a crucial role in optimizing interactions between surfaces and their environments, enabling control over contact processes such as wettability, friction, adhesion, and hydrodynamic resistance. Numerous studies have examined natural surface textures to understand their influence on these processes (Arzt et al., 2021; Barthlott et al., 2017). Living organisms have evolved textured surfaces as adaptive strategies, demonstrating the potential of engineered textures to replicate or enhance these natural properties.

One notable phenomenon influenced by surface texturization is wettability, which describes the interaction between a solid and water. For example, the lotus flower [210] and shark scales [211] exhibit microscale textures that confer superhydrophobic properties. Superhydrophobic surfaces display high water repellence, with contact angles exceeding 150 degrees, leading to self-cleaning effects, reduced hydrodynamic resistance, and decreased adhesion of substances [212, 213].

The potential applications of superhydrophobic surfaces extend to biomedical engineering, particularly in enhancing the hemocompatibility of blood-contacting implants such as arterial stents, heart valves, and annuloplasty devices [214]. By minimizing hydrodynamic resistance and preventing the adhesion of platelets, proteins, or lipids, these surfaces can reduce thrombosis formation, delay restenosis, and lower the need for cardiovascular medications [215].

The research explores two primary applications of NPAM technology:

- Extrusion-based 3D printing, where precise material deposition along curved trajectories facilitates three-dimensional textures that enhance functional surface properties.
- Chemical etching, which adapts the same trajectories to guide controlled etching processes on metallic or polymeric materials.

Chemical etching is a widely used technique for surface modification, enabling precise control over texture depth, roughness, and functionalization. Various etching methodologies, such as acid etching [216], electrochemical etching [217], and plasma etching [218], have been employed to modify tribological properties, improving wear resistance and lubrication. The integration of chemical etching with NPAM introduces significant advantages, particularly for non-planar surfaces. The ability to guide etching along complex trajectories ensures homogeneous texturing, even on surfaces with variable curvature, overcoming limitations associated with traditional planar etching processes. This approach enhances surface functionality in applications such as biomedical implants, mechanical seals, and high-performance tribological interfaces by providing customized textures optimized for specific operational conditions.

Several case studies are presented involving surfaces such as cylinders, surfaces with positive and negative curvatures, and platforms with variable curvature. The automation of trajectory generation for these manufacturing processes is assessed in terms of precision and efficiency, highlighting the seamless integration potential of NPAM with advanced manufacturing workflows. The results demonstrate that combining NPAM with robotic systems can broaden the scope of additive manufacturing applications, offering innovative solutions in industrial design, biomedical engineering, and tribological contact engineering by enhancing surface texturing capabilities for modern, high-performance applications.

Geometry definition: texture and build platform.

The texture modeled in this case study corresponds to the well-known "shark-skin" texture. The texture has been scaled to dimensions of $2[mm]$ in length, $1[mm]$ in width, and $0.5[mm]$ in height, aligning with the lower manufacturable limits of commercial additive manufacturing systems. The textures are mounted on a rectangular base, which is subsequently mapped onto various axisymmetric surfaces with a height of $12[mm]$ and a width of $7[mm]$. Figure 7.16 illustrates the base component used in this case study.

The defined texture must be mapped onto four base surfaces, arranged from simplest to most complex: cylindrical, positively curved, negatively curved, and combined curvature surfaces. In all four cases, using the trihedron $\{e\}$ defined for slicing space as a reference, the mean curvature radius in the $\theta-$direction is maintained at $1.5[mm]$. This ensures that the base geometry conforms to the mean circumference of the print bed, minimizing deformation in the $\theta-$direction.

As explained in previous chapters, the DfNPAM process involves not only the geometric

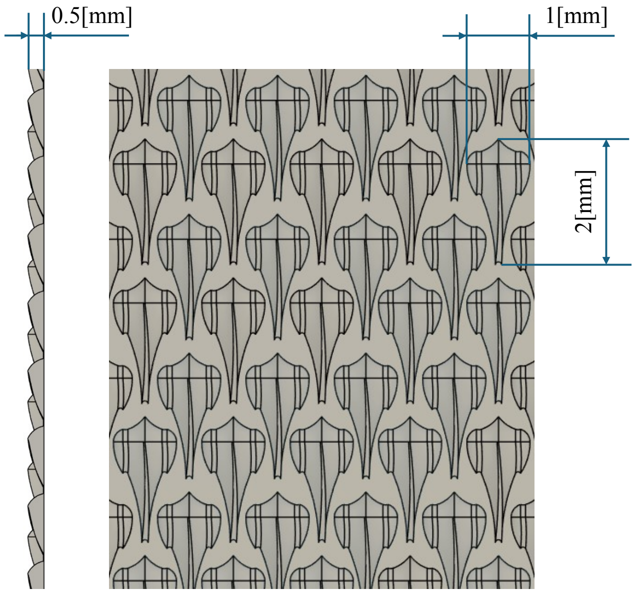

Figure 7.16: Shark-skin texture geometry used in the execution of the case study.

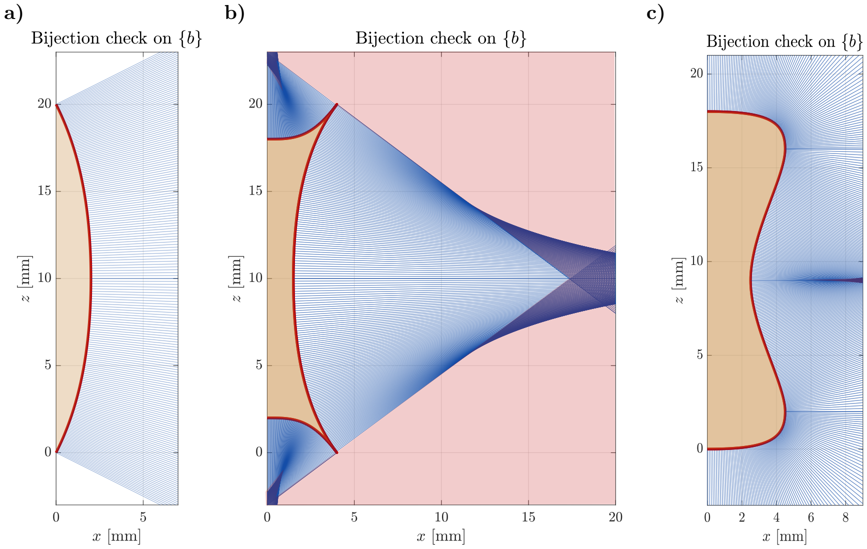

Figure 7.17: Bijection evaluation in the proposed curved design spaces. a) Positive curvature surface. b) Negative curvature. c) Combined curvature surface. Red areas represent non-bijective regions of the space transformation.

definition of design spaces and their mapped surfaces but also an assessment of feasibility at the build platform level. In the cylindrical case, prior examples have demonstrated that the bijectivity of the mapping process is always preserved. However, for cases involving curvature in the $L-$direction, it is necessary to evaluate the regions where bijectivity holds within the design space. Figure 7.17 presents an evaluation of bijectivity zones for the three cases of curvature in the $L-$direction.

Once all mapping geometries and textures have been defined, the designs are generated in space $\{b\}$ and mapped onto various interior and exterior revolution surfaces. They are then sliced for non-planar robotic additive manufacturing. Furthermore, this method also generates the required toolpaths for the nozzle to construct the part, including travel movements and retractions inherent to the manufacturing process.

For non-planar additive manufacturing paths, waypoints are generated using Ultimaker Cura, a commercial slicing software. Initially, toolpaths are mapped onto a flat surface in $\{e\}$ using the input geometry defined in Figure 7.16. These toolpaths are subsequently transformed into Cartesian space, resulting in curved trajectories in $\{b\}$.

In the case of chemical etching, a point distribution algorithm is employed to ensure uniform coverage of the target surface by mapping it with equidistant points. This algorithm guarantees complete and homogeneous surface coverage with a predefined point density. The distribution is achieved through a repulsion-based approach within slicing space $\{e\}$ over the parametrically defined build platform. Once the distribution is established, the point pattern is traversed, depositing the chemical etchant at the designated positions, which are then transformed into Cartesian space $\{b\}$.

Unlike the layer-by-layer deposition approach in non-planar additive manufacturing, etching modifies the surface through chemical attack rather than material addition. This means that the target geometry is treated as a whole, with points distributed evenly across its surface to ensure consistent chemical processing.

In this case, a shark-fin profile has been mapped onto a convex curvature surface. After point distribution, a toolpath is generated for the chemical agent dispenser to follow. At each point along this trajectory, a droplet of the chemical agent is deposited. The toolpath is computed using the algorithm developed in Chapter 5, excluding contours, as they do not provide relevant information for this manufacturing method.

This chemical etching methodology is designed to be executed using the same setup as the non-planar additive manufacturing process described in Chapter 5, with the printhead replaced by a syringe-based droplet dispenser. This setup is suitable for both masked and maskless chemical etching. Additionally, it could potentially be adapted for plasma jet applications by replacing the syringe with a needle connected to a high-voltage source while using the curved metal surface as the ground electrode.

In all cases, each point along the toolpath must be carefully defined to ensure that droplet or jet expansion remains within contour boundaries while also being deposited vertically in alignment with gravity. For this reason, a fixed dispenser setup combined with a mobile bed mounted on a robotic arm is the ideal configuration for this application.

7.3.2 Results and discussion

The following section presents the results of the case study, focusing first on texture mapping across different surfaces. Figure 7.18 illustrates the texture mapping on four surfaces: cylindrical, convex, concave, and mixed-curvature build platforms. The results demonstrate how the procedure effectively adapts the texture to the predefined surface geometries. Due to the absence of interference in the non-bijective regions, the algorithm does not exhibit convergence issues.

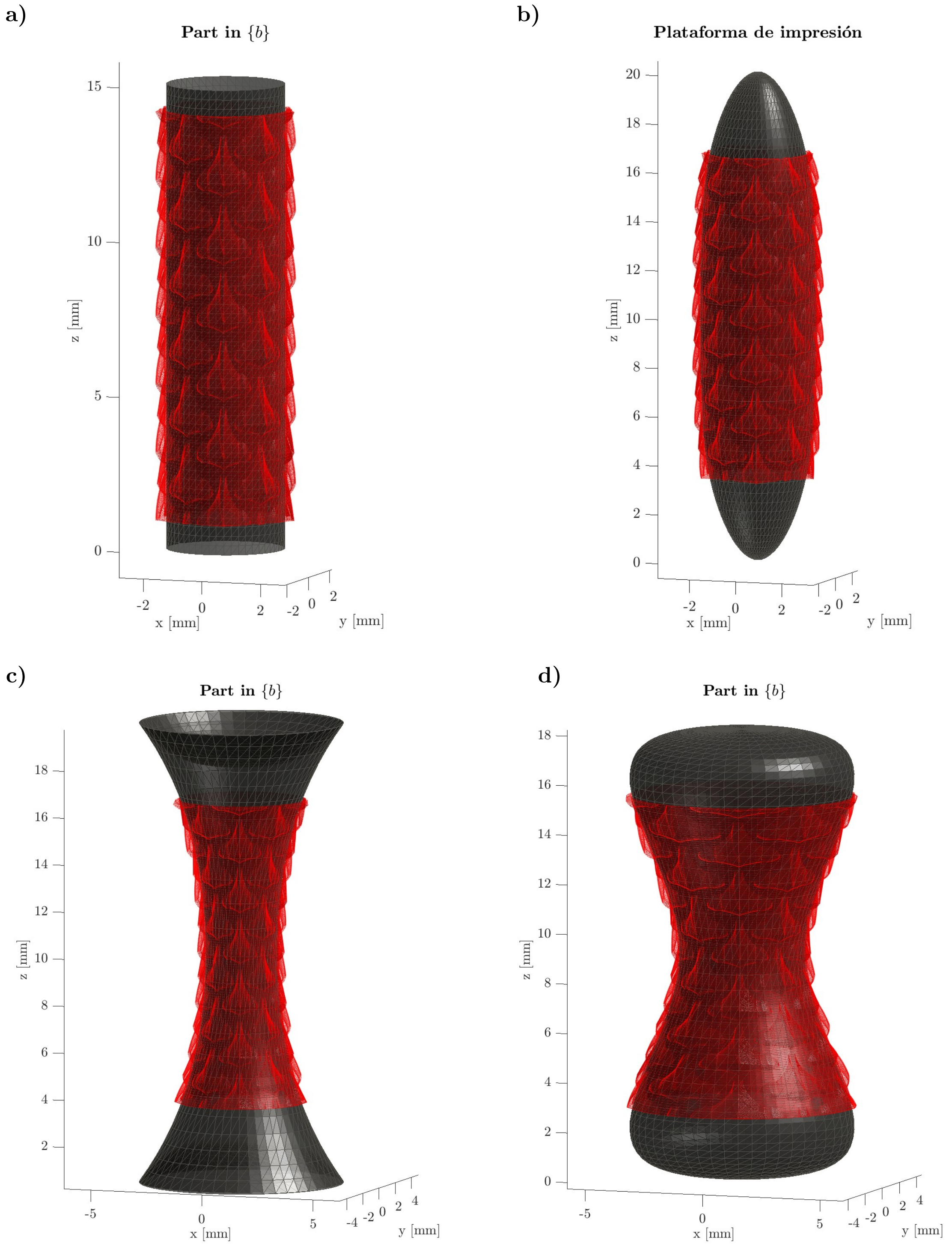

Figure 7.18: Texture mapped in the outter side of four different surfaces: a) Cyllinder, b) Positive curvature surface, c) Negative curvature surface, and d) combined curvature surface.

In all cases, a texture deformation consistent with the expected curvature is observed in both the L and $\theta-$directions. This methodology proves particularly useful for surfaces with low curvature, as evaluated, or for cases with a single curvature in the $\theta-$direction. In this latter case, deformation can be corrected by adjusting the texture distribution to match the base cylinder's diameter.

Using the cylindrical case, the mapping validation was performed for the same surface but on its interior, simulating a textured cylindrical duct. In this study, it is assumed that the texture must be printed in multiple sections due to the robot arm's inability to access the interior of a closed cylinder. However, such textures are highly relevant for heat transfer applications in addition to the previously mentioned cases.

The results are presented in Figure 7.19, confirming that by redefining the direction of the build platform's control points—starting from the bottom upward and orienting the trihedron internally—this geometry can be successfully achieved.

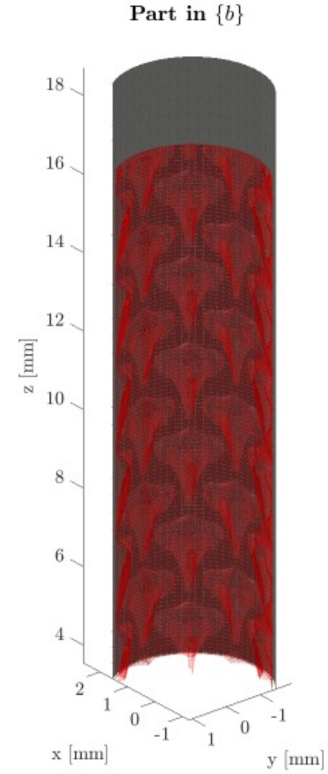

Figure 7.19: Texture mapped in the inner side of a cylindrical build platform.

NPAM trajectory generation

Once the target geometries for mapping are obtained, the base geometry is processed to generate non-planar additive manufacturing toolpaths using Ultimaker Cura. The process begins with the planar toolpaths generated by Cura, which produces a standard G-code for flat additive manufacturing. This G-code is then analyzed to identify the waypoints that define the planar trajectory.

These waypoints are repositioned within the slicing space according to the desired geometry and are subsequently transformed back into Cartesian space for each build platform. Figure 7.20 presents the results of the toolpath generation process in $\{e\}$. It illustrates how Cura's toolpaths are adapted into trajectories within the $\{e\}(L, \theta, H)$ space through G-code analysis. Subsequently, these trajectories are scaled to match the dimensions of each build platform or, in this case study, the mapping surface.

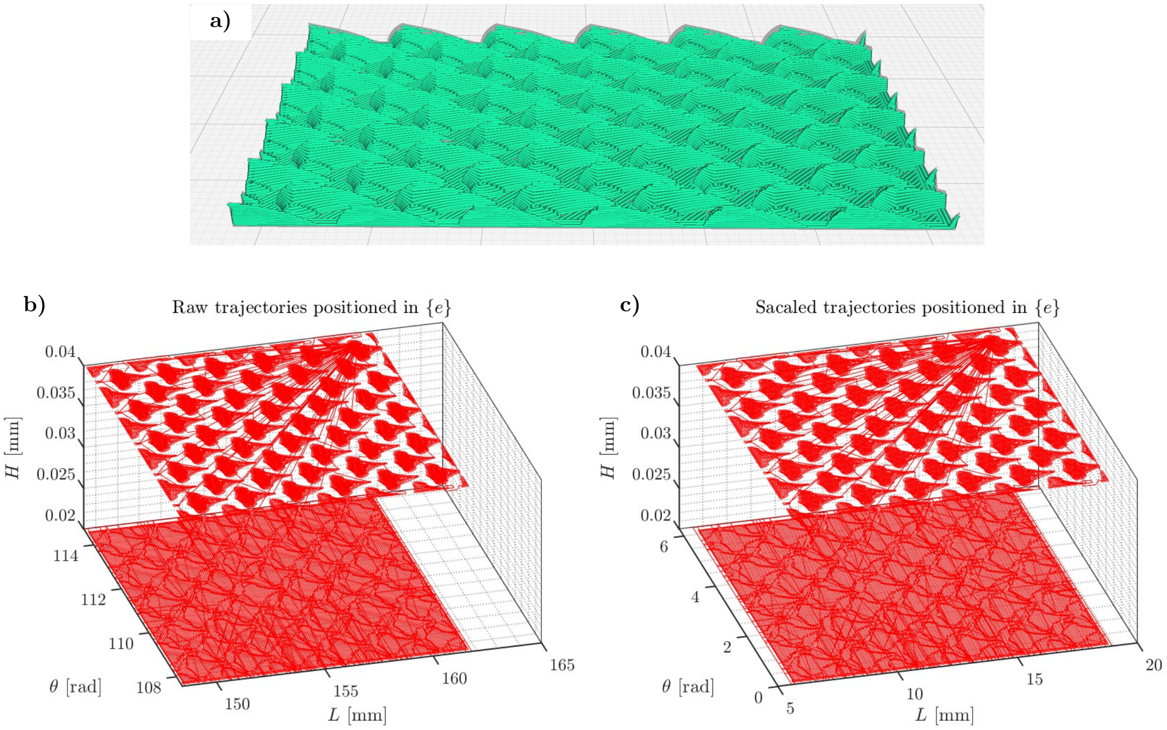

Figure 7.20: The trajectory generation and transformation process prior to final surface mapping. a) planar trajectories in Carthesian space designed by Cura. b) Non scaled planar trajectories in the slicing space $\{e\}$. c) Scaled planar trajectories in the slicing space $\{e\}$ according to its final platform transformation.

Once the trajectories have been processed, the results of each processed file in $\{e\}$ is mapped onto its corresponding build surface in $\{b\}$, generating the robot's waypoints in both position and orientation relative to the SR Fusion reference system. Figure 7.21 presents the results for the four considered cases with different surface types. It can be seen how this methodology ensures that extrusion paths, retractions, and speed change information are preserved across spaces, allowing direct input into the control system of the non-planar additive manufacturing robotic station.

Chemical etching trajectory generation

Once the trajectory design for non-planar additive manufacturing is completed, the focus shifts to designing a toolpath for chemical etching. To achieve this, the target profile is extracted from the shark-fin geometry. After isolating it on a concave surface, a point-repulsion algorithm is applied to define the trajectory's waypoints, ensuring a uniform deposition of the

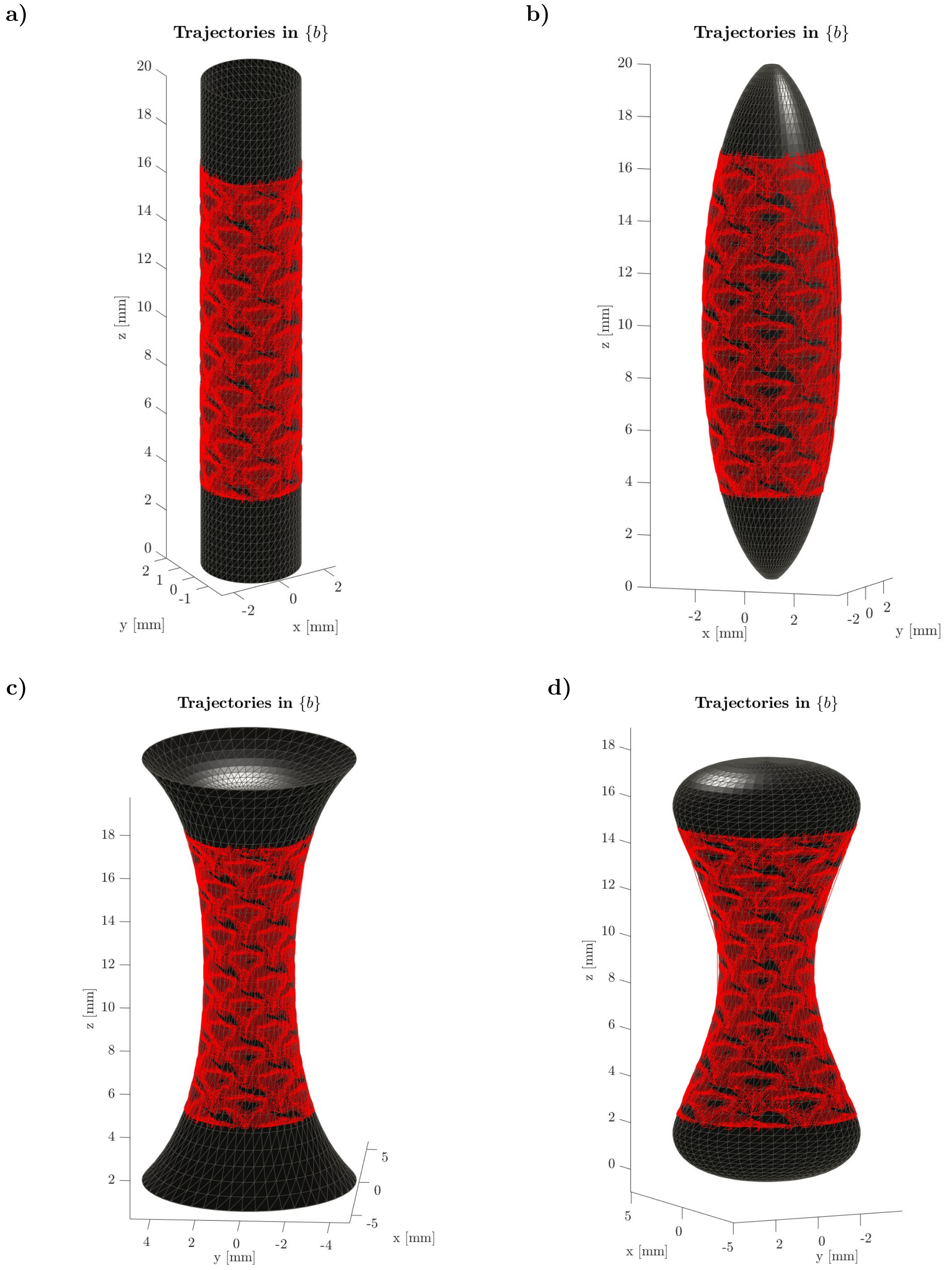

Figure 7.21: Final trajectories displayed on the Carthesian space referred to the robot's TCP, $\{b\}$. a) Cyllinder, b) Positive curvature surface, c) Negative curvature surface, and d) combined curvature surface.

chemical agent. Figure 7.22 illustrates the outcome of this procedure in spaces $\{e\}$ and $\{b\}$.

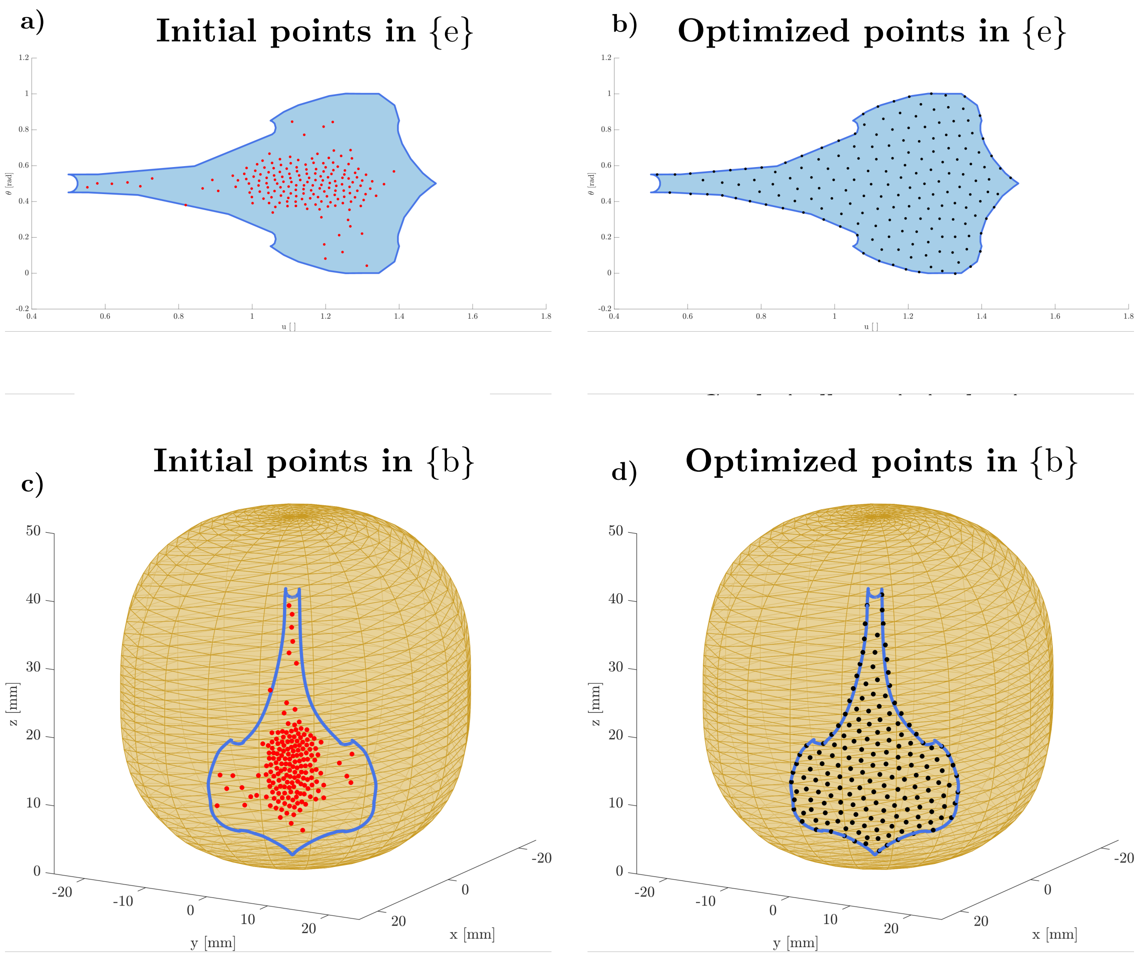

Figure 7.22: Point homogeneous distribution for shark fin texture chemical etching on a convex surface. a) Initial seed in $\{e\}$, b) Final distribution in $\{e\}$, c) Initial seed in $\{b\}$, and d) Final distribution in $\{b\}$.

Finally, using the point-connection algorithm developed in Chapter 5, a toolpath has been designed to map the geometry and enable chemical etching with a homogeneous point density. Figure 7.23 illustrates the obtained result.

To achieve higher definition, the point density must be increased, as the current resolution is relatively low. However, the chosen definition level must align with the minimum volume of chemical agent that the syringe can dispense. Otherwise, excessive resolution may cause droplet overlap, blurring the result instead of enhancing precision.

The successful resolution of curved trajectory generation in these two case studies validates the applicability of the methodology not only for additive manufacturing toolpaths but also for any operation performed along a non-planar surface. This is achieved through the definition of an embedded mapping, where a planar working subspace $\{e\}$ is transformed back to yield the final trajectories.

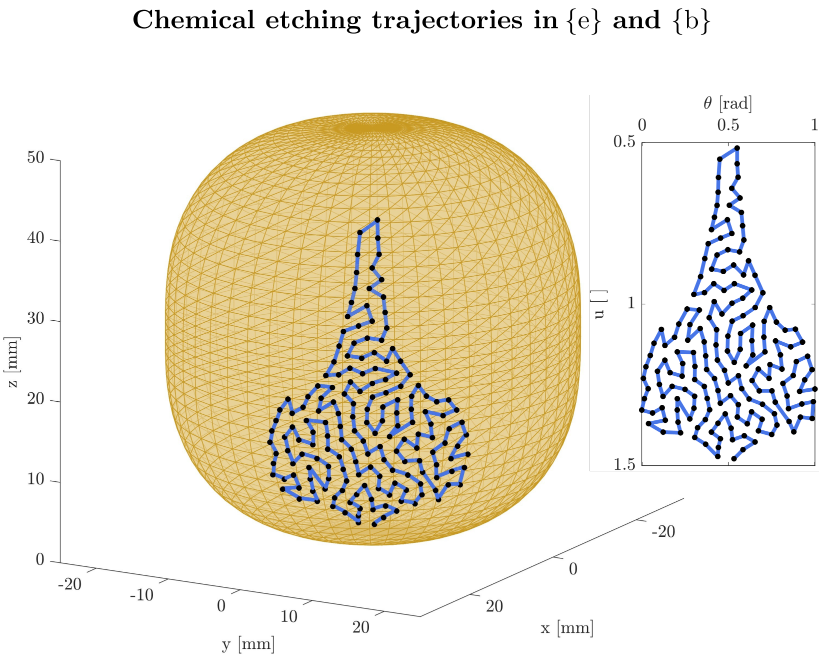
Chemical etching trajectories in {e} and {b}

Figure 7.23: Chemical etching generated trajectory to generate shark.fin textures on a convex surface.

7.4 Additive manufactured forming die performance optimization

7.4.1 Case study description

Additive manufacturing for sheet metal forming matrix has garnered increasing attention due to its potential to offer design flexibility, rapid prototyping, and efficient material usage. However, implementing AM in mold fabrication presents unique challenges, particularly in meeting the mechanical and structural demands of deep-drawing processes. Traditional mold materials like steel possess well-established properties to withstand the high stresses associated with deep drawing, but AM-fabricated molds—often relying on polymer or metal powders with layered structures—can be prone to specific failure modes due to differences in material composition, layer adhesion, and structural anisotropy [219, 220, 221].

One of the primary challenges in AM-fabricated molds is handling stress distribution under load. AM processes typically produce materials with anisotropic mechanical properties, where the strength and stiffness vary with the build orientation. This anisotropy can result in failure when molds face multiaxial stresses from complex drawing shapes, leading to deformations, cracks, or even catastrophic failure if stresses align with weaker directions in the material structure. Additionally, the layer-by-layer nature of AM introduces potential for defects such as porosity or inter-layer weak spots, which reduce the material's capacity to withstand high stresses required for reliable deep drawing.

To improve the performance of AM matrices, it is crucial to optimize both material selection and build orientation. Materials with enhanced interlayer bonding. Aligning the build orientation with the expected stress trajectories can further reinforce the structure, as the layers are then positioned to best resist the anticipated forces. Anisotropic designs, where the mold's primary load-bearing elements align with the stress paths, could significantly mitigate stress concentrations and minimize the risk of cracking under load.

Throughout a preliminary study, we validated the feasibility of conducting deep-drawing processes using additive manufacturing (AM) techniques with molds produced from Tough PLA and a 0.5 mm thick aluminum sheet. Our initial findings confirmed that Tough PLA molds can sustain the fundamental requirements of deep-drawing for thin aluminum sheets, offering an affordable and accessible solution for rapid prototyping and low-volume production. However, while these molds proved capable of achieving basic forming, challenges such as mold wear, deformation under load, and limited resilience to repeated use were evident. Addressing these limitations is essential for advancing the reliability and longevity of AM-fabricated molds in more demanding industrial applications. Figure 7.24 illustrates the results of the validation test for deep drawing an aluminum sheet using a Tough PLA mold prior to the removal of any excess burr.

Figure 7.24: Sheet metal forming validation. Cylindrical shape formed using a Tough PLA matrix using 0.5[mm] thicknes AW1050 aluminum sheet.

To enhance the performance of Tough PLA molds, this case study focuses on implementing a DfNPAM methodology. By refining the geometric structure and strategically reinforcing stress-bearing regions of the mold, DfNPAM seeks to optimize the mold's response to the mechanical loads exerted during stamping. This approach involves analyzing stress distributions within the mold matrix to determine the most vulnerable points of deformation and adjusting the design to distribute loads more effectively. DfNPAM's targeted improvements aim to bolster the matrix's ability to absorb and dissipate stresses without succumbing to structural failure, ultimately enhancing the mold's durability and functional lifespan.

By employing DfNPAM for Tough PLA molds in this study, we aim to develop a structured framework for improving mold robustness and reliability in AM applications for sheet metal forming. The proposed adjustments not only address the material's inherent limitations but also provide insights into optimizing AM mold designs for broader applications within the metal-forming industry.

Characterization of the component in use

The initial phase of this case study involves characterizing the deep-drawing mold to understand the primary stresses exerted during the process, with the goal of optimizing mold fabrication. This mold is specifically designed for forming cylindrical cups with a target geometry of $50[mm]$ in diameter, $20[mm]$ in height, and a rounded edge radius of $2.5[mm]$ on the inner surface and $3[mm]$ on the outer surface of the finished part. Figure 7.25 illustrates the intended geometry, which serves as the benchmark for evaluating the mold's performance and structural response under load. Understanding the stress distribution within this target geometry is crucial for refining the mold design to prevent deformation, enhance durability, and ensure dimensional accuracy in the final component.

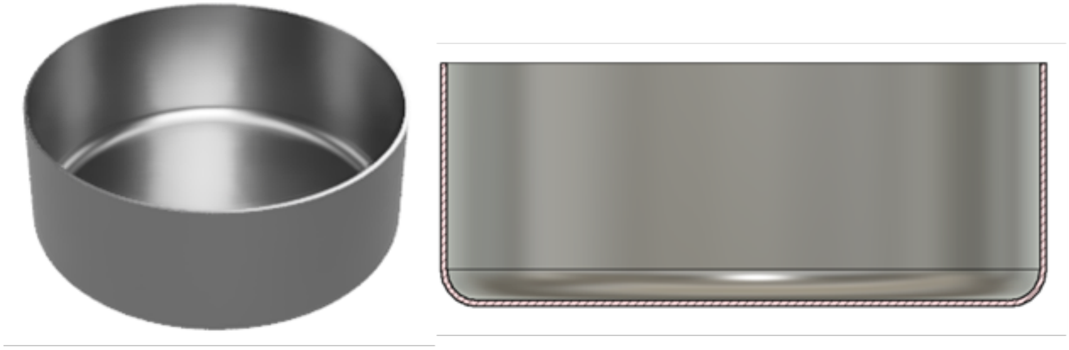

Figure 7.25: Sheet metal forming part design.

Following the characterization and optimization process, the finalized mold design, as shown in Figure 7.26, consists of three main components, each carefully engineered to fulfill specific functional requirements. The first component is a rigid die, which serves as the primary structural element and provides the necessary stiffness to maintain dimensional stability during the drawing process. This shape is designed not only for structural integrity but also for ease of assembly and disassembly, which allows for maintenance and adjustments without compromising the alignment and precision of the mold.

The second component is a clamping mechanism, known as the blank holder, which is threaded into the die. This blank holder secures the aluminum sheet in place and applies controlled pressure to minimize wrinkling or slippage during deep drawing. The blank holder is designed with adjustable threading to accommodate different sheet thicknesses, providing versatility and ensuring that the sheet remains firmly held throughout the process, which is critical for achieving consistent forming results.

The third and final component comprises interchangeable mold walls, which endure the majority of the mechanical loads exerted during the drawing process. These walls are specifically designed to be replaceable, allowing for tailored wear resistance and enhanced durability, as they can be substituted independently when wear or fatigue occurs. The wall segments are fabricated to withstand the compressive and tensile stresses that arise during deep drawing, particularly at the critical regions where the material is shaped and stretched. This modular approach not only extends the mold's operational life but also provides flexibility to adapt the mold for different geometries by replacing only the wall sections, significantly reducing manufacturing costs and enhancing the mold's functional adaptability.

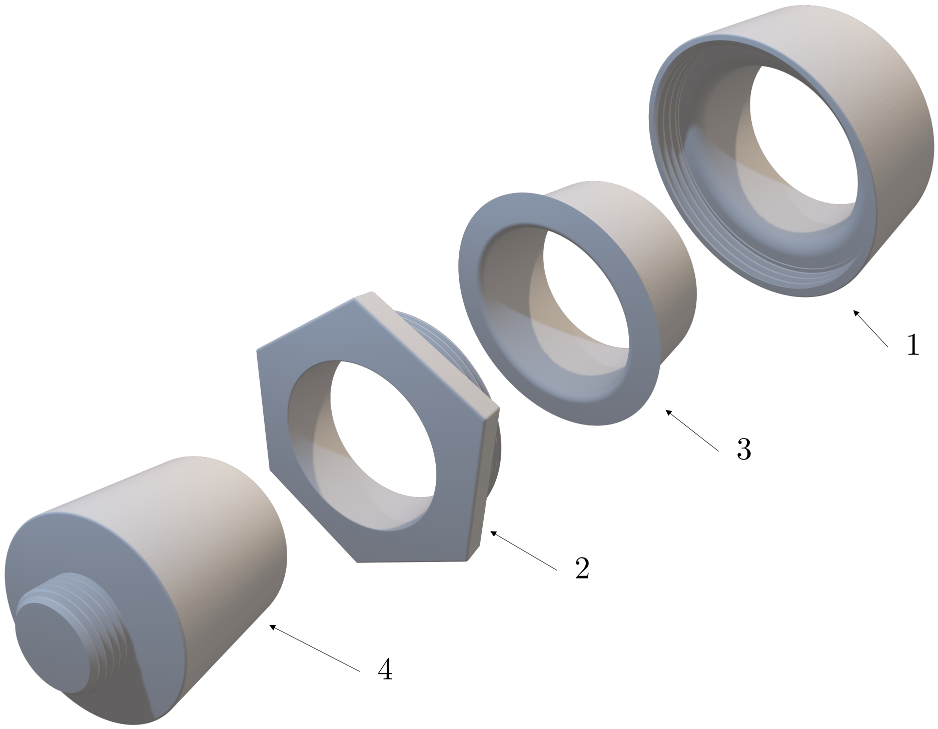

Figure 7.26: Tooling used in the deep-drawing process of the target part.

The fourth and final component is a cylindrical punch, which plays a critical role in shaping the aluminum sheet by applying force to press it into the mold cavity. This punch is precisely engineered to ensure smooth and uniform deformation of the sheet, pushing the material downwards against the mold walls to achieve the desired cylindrical form. Made from a durable material to withstand high compressive stresses, the punch must be dimensionally accurate, with a diameter matching the inner dimensions of the intended cylindrical cup. The punch's surface finish is also optimized to reduce friction during contact with the sheet, minimizing the likelihood of surface imperfections or tearing in the aluminum. Additionally, the alignment of the punch within the mold assembly is essential, as any misalignment can lead to uneven distribution of force, which would cause defects such as wrinkling or thinning of the material. The punch's interaction with the sheet is calibrated to deliver sufficient pressure to shape the aluminum without exceeding its plastic deformation limits, ensuring that the material flows smoothly into the mold while maintaining its structural integrity.

The mold and die assembly are secured within a hydraulic press, which provides the necessary force to transform the aluminum sheet.

Determination of the optimal layer distribution

Due to its direct contact with the metal sheet and its role as the most critical component in this additive manufacturing case study, it was decided to optimize component 3 using

Non-Planar Additive Manufacturing (NPAM) techniques. Given the available optimization approaches, the primary focus will be on enhancing the component's ability to withstand stresses during the deep-drawing process. By prioritizing stress optimization, the goal is to improve the component's structural resilience, reducing the risk of deformation and increasing its operational lifespan.

In addition to stress optimization, the final design will also aim to achieve a high-quality surface finish, which is essential for minimizing defects in the formed part. A smooth surface reduces friction and helps ensure that the metal sheet flows evenly across the mold, preventing common issues such as surface imperfections, thinning, or wrinkling in the aluminum. This is particularly crucial given that PLA, due to its relatively low hardness, is prone to deformation when subjected to high stress. To counteract this limitation, NPAM strategies will be employed to optimize both the geometry and layer orientation of the component, enhancing its structural integrity and providing a surface finish that supports high-quality results in the final formed part. Through this dual-focus approach, the study seeks to balance mechanical performance with surface quality, ensuring that the component performs reliably while minimizing potential defects.

Based on simulations conducted for the deep-drawing process, the primary load borne by component 3 consists of radial expansion pressure exerted by the aluminum as it is formed, combined with a superficial shear load that progressively extends across the entire component. This load distribution, under ideal conditions, is axisymmetric along the length of component 3, aligning with the cylindrical geometry of the part. The radial pressure results from the aluminum sheet pressing outward as it conforms to the mold shape, creating a uniform expansion force around the inner surface of the component.

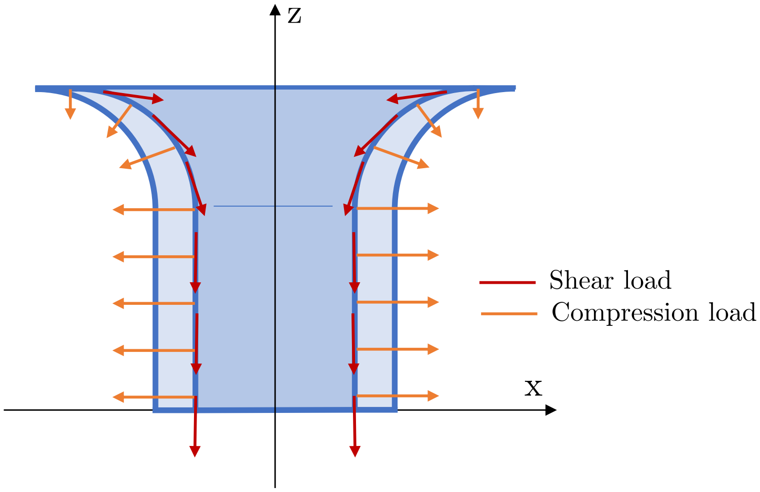

Figure 7.27: Load distribution over the volume of the studied component. Shear stress on the deep-drawing surface is shown in red, and radial compression of the component is shown in orange.

Additionally, the shear load arises from the relative movement between the aluminum sheet and the mold surface, which is a critical factor as it extends the stresses along the entire surface of the component. This shear stress builds gradually as the aluminum is drawn into the mold, requiring the material to have both sufficient tensile strength and surface durability to prevent failure under repeated cycles. Figure 7.27 represents these loads in a cross-sectional view of component 3, illustrating the radial and shear forces as they distribute symmetrically. Understanding this load distribution is essential for optimizing the design and material selection of the component, ensuring it can reliably withstand the applied stresses controlling its damage during the deep-drawing process.

After analyzing the stress state across various regions of the material, an axisymmetric layer configuration is proposed to enhance the component's load-bearing capabilities. This configuration is designed to work in compression along the stacking direction of the layers, addressing the most unfavorable loading condition, and in tension along the surface where shear stress is highest. By aligning the layers to withstand compression in the critical stacking direction and to provide tensile strength at the surface, this configuration aims to improve the component's resilience under the specific stresses encountered during deep drawing.

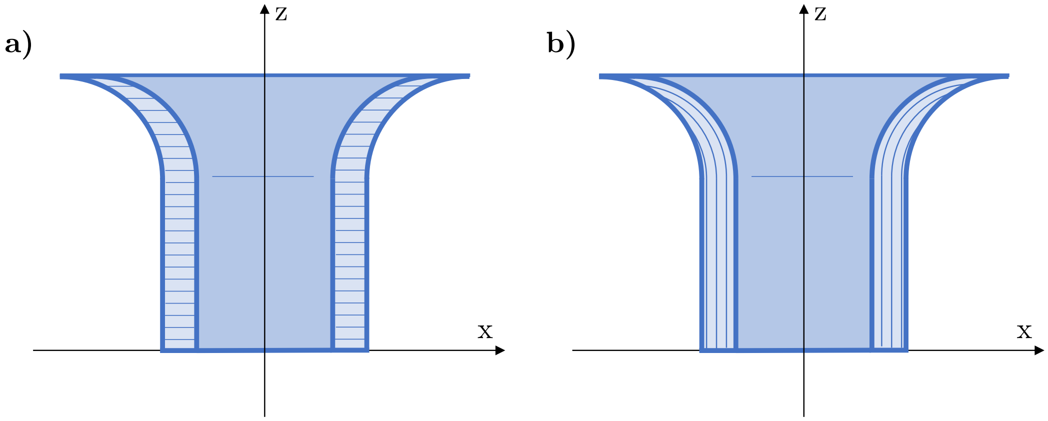

Figure 7.28: Layer distribution on component 3. a) Planar additive manufacturing. b) Non-Planar additive manufacturing.

Figure 7.28 presents a comparative view of the resulting geometries between components fabricated using planar additive manufacturing and non-planar additive manufacturing. The non-planar approach yields a geometry better optimized for the functional demands of the part. In non-planar fabrication, layer alignment and orientation can be adapted to the complex stress distribution, effectively minimizing weaknesses caused by layer delamination or misalignment under high loads. It is through this analysis of the component under its working load that the print bed is defined, which will generate the non-planar layers that optimize the geometry to be constructed.

7.4.2 Results and discussion

Based on the comprehensive study conducted on component 3 of the aluminum sheet deep-drawing system, it has been proposed to laminate the component using the custom software developed in Chapter 4 of this thesis. Within the software, the spline curve that best approximates the interior surface of the component is introduced as the generative curve. This spline serves as the guide for the stacking process, resulting in the formation of the desired non-planar layers.

The software allows precise control over the curvature and alignment of each layer to optimize load-bearing capacity and stress distribution across the part.

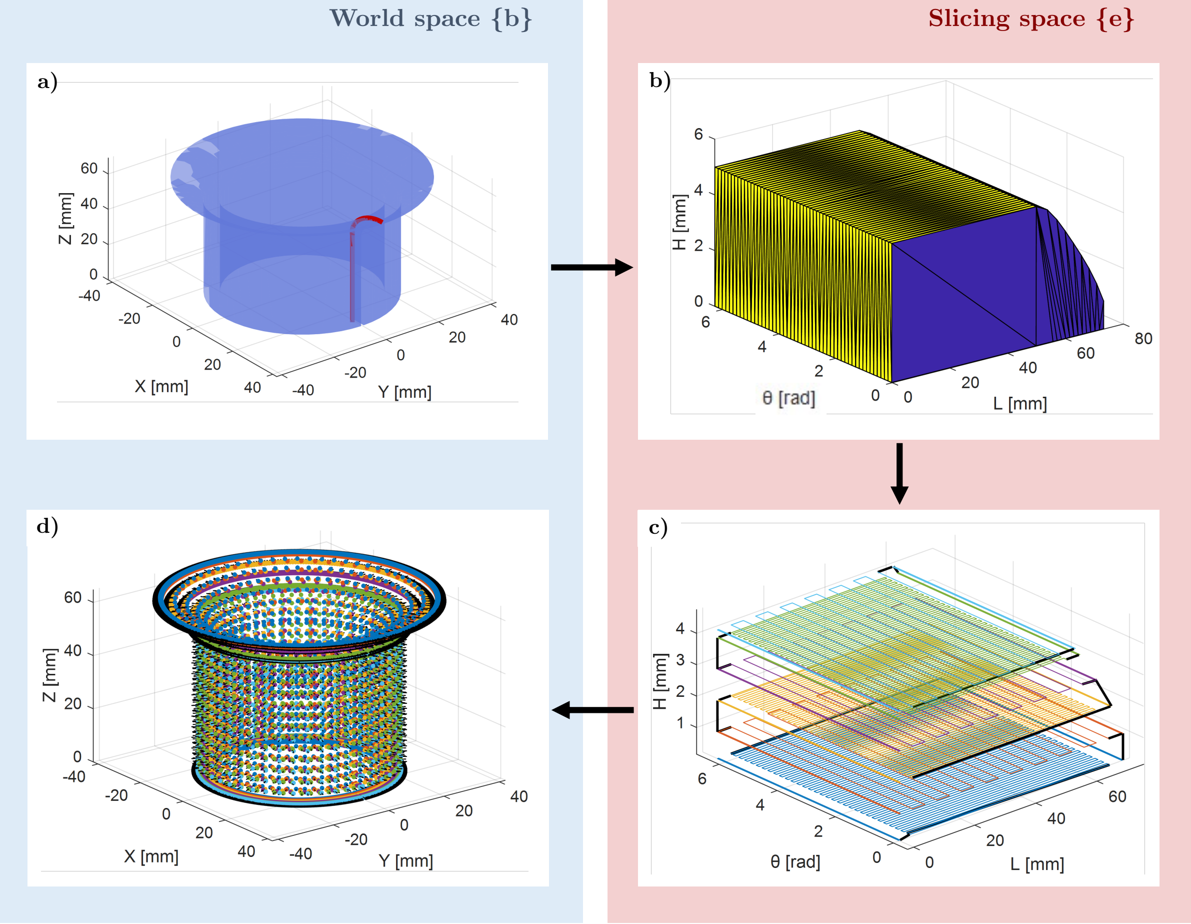

Figure 7.29: Result of the lamination of component 3. a) STL part positioned relative to its print bed. b) STL part transformed into the slicing space $\{e\}$. c) Laminated solid with trajectories generated in $\{e\}$. d) Printing trajectories in the world space $\{b\}$.

Figure 7.29 summarizes the global inputs and outputs of the software. The inputs include the STL part and the pre-defined base bed, while the outputs are the trajectories in the world space referenced to frame $\{b\}$.

To enhance the visibility of the layers and the influence of their infill direction, Figure 7.30 has been developed. This figure illustrates how the infill of each layer has been oriented to optimize the material's strength and ensure the proper execution of the deep-drawing process.

In this figure, odd-numbered layers are laminated along the $L-$direction for two primary reasons. First, this orientation provides maximum material strength in the L direction, which is crucial for withstanding the tensile stresses exerted during the aluminum sheet forming process. Second, it facilitates the smooth flow of the aluminum sheet during the drawing process, reducing the likelihood of defects such as wrinkling or tearing.

In contrast, even-numbered layers are laminated along the $\theta-$direction. This approach

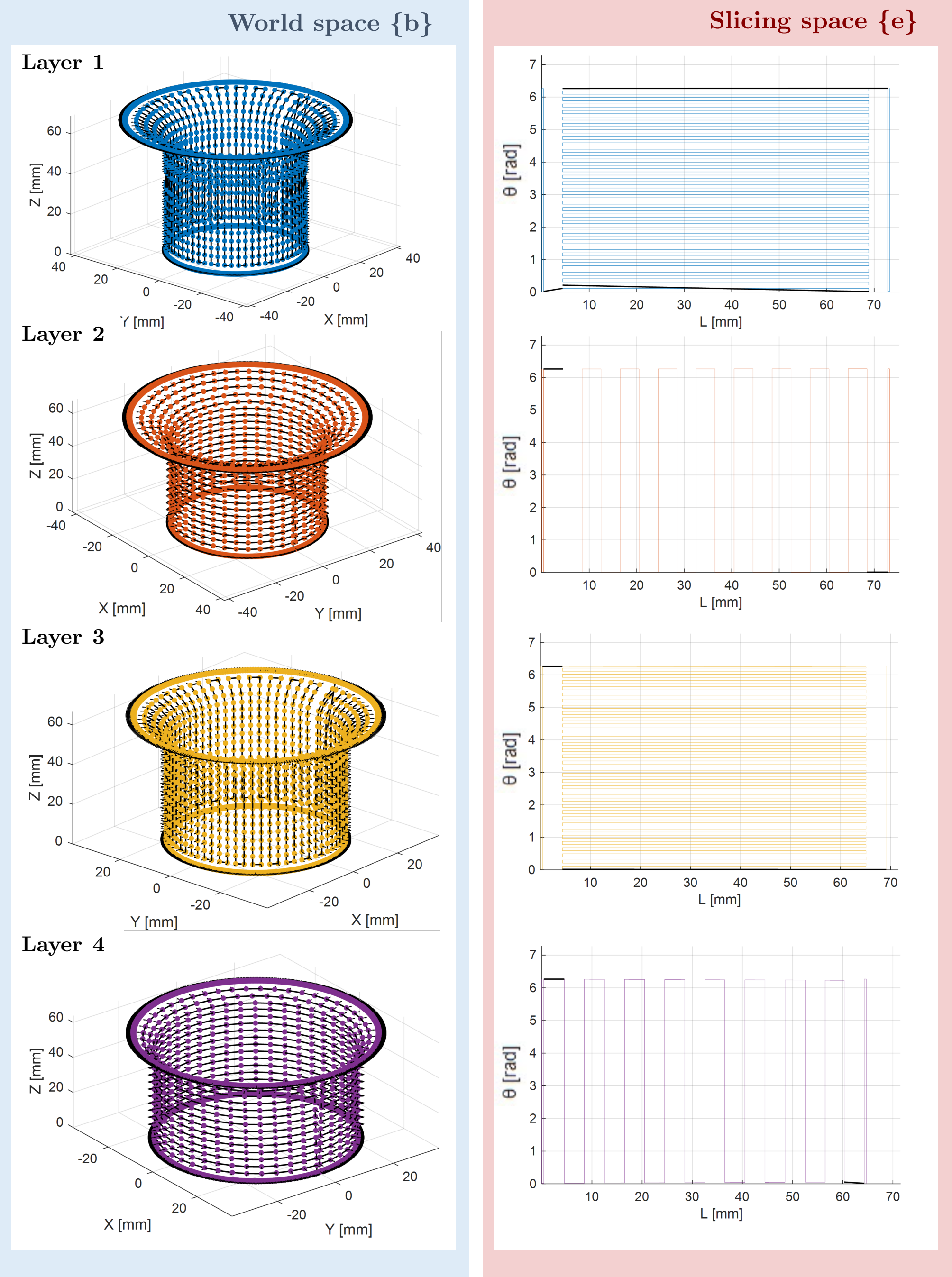

Figure 7.30: Detail of the lamination result for the first four layers of component 3. Odd-numbered layers are shown with infill oriented in the direction favorable for resisting surface shear stress, while even-numbered layers form concentric rings to support the compressive forces on the component.

leverages concentric rings to enhance the component's resistance to compressive forces, which are predominant during the deep-drawing operation. By alternating the lamination directions between L and θ, the design ensures that the component maintains optimal performance under both tensile and compressive loads, balancing the mechanical demands imposed during the forming process and improving the overall durability of the part.

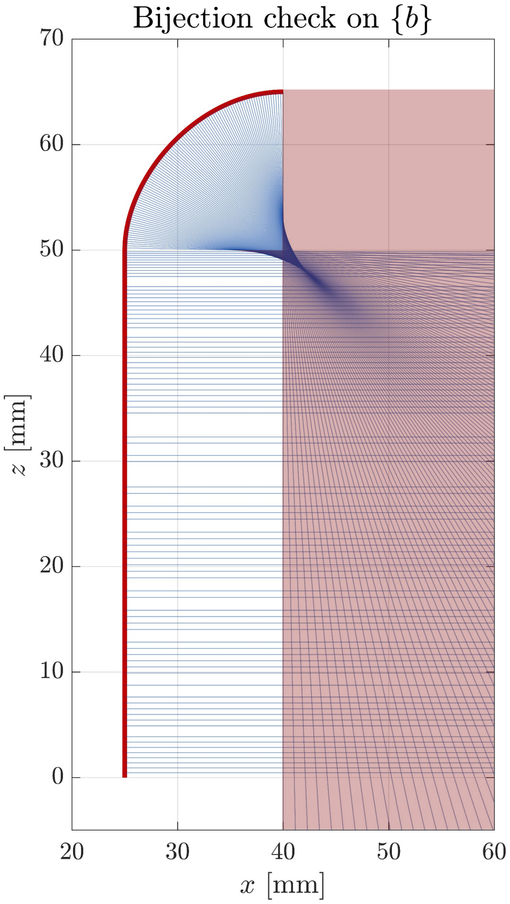

Figure 7.31: Determination of the bijectivity area of the transformation associated with the base curve proposed for the case study development. The non-bijective region is highlighted in red.

To validate the feasibility of fabricating the component, a bijectivity check was performed to ensure its printability on the assigned print bed. This analysis focused on identifying any geometric constraints that could prevent successful manufacturing. As shown in Figure 7.31, the width of the interchangeable wall in the system cannot exceed a specific threshold, as this would make it impossible to fabricate using the defined additive manufacturing process. Consequently, the maximum wall thickness becomes a critical design parameter, ensuring both structural integrity and manufacturability. This constraint highlights the importance of balancing functional requirements with process limitations in the design phase. This threshold imposes a maximum component thickness in the $x-$direction of approximately $10[mm]$, which is greater than the proposed design thickness.

Furthermore, the setup of the component on the print bed was carefully evaluated to facilitate its post-print extraction. Figure 7.32 illustrates the optimized placement, demonstrating that the curved portion of the component must be oriented towards the side where the robotic arm holds the end effector. This orientation minimizes interference during removal and ensures that the robotic system can effectively handle the part without damaging it. This insight underscores the necessity of integrating considerations of robotic handling and post-processing into the early stages of design, particularly for complex geometries fabricated using advanced additive manufacturing techniques.

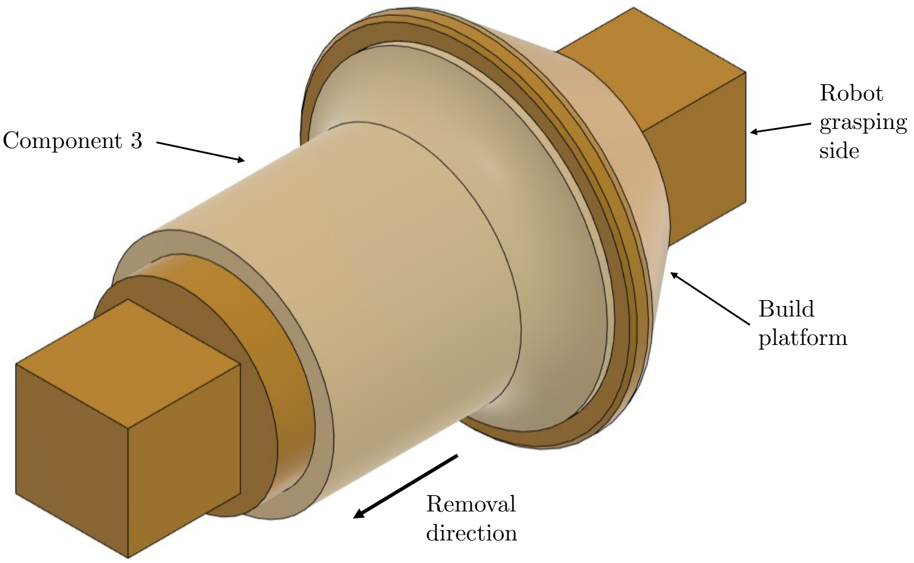

Figure 7.32: Placement of component 3 on the curved build platform for non-planar additive manufacturing. The robot grasping side and the removal direction are shown.

This case study demonstrates the potential of Non-Planar Additive Manufacturing (NPAM) techniques to overcome challenges in the fabrication of molds for deep-drawing applications, particularly when employing Tough PLA. By leveraging NPAM, component 3 was optimized to better withstand the unique stresses encountered during the forming process, including radial compression and surface shear. The anisotropic layering strategy tailored to align with these stress trajectories not only improved the structural resilience of the component but also addressed limitations inherent to planar additive manufacturing, such as layer delamination and suboptimal load distribution.

Despite these advancements, it is important to acknowledge that Tough PLA, while offering sufficient mechanical properties for low-volume production and rapid prototyping, lacks the hardness and durability of traditional mold materials like aluminum. Consequently, component 3 will likely require periodic replacement due to surface wear induced by repeated contact with the aluminum sheet. However, the optimized NPAM strategy ensures that the component primarily suffers surface damage rather than structural failures, allowing for continued performance until surface degradation necessitates replacement.

Additionally, the bijectivity check ensured that the component's geometry was manufacturable within the constraints of the assigned print bed, reinforcing the importance of integrating manufacturability analyses early in the design process. Furthermore, practical considerations for robotic handling were incorporated, enabling efficient post-process removal of the component from the curved build platform. These findings emphasize the necessity of balancing material performance, stress management, and operational practicality. Future efforts should focus on enhancing the surface wear resistance of Tough PLA molds to extend their operational lifespan and broaden their applicability to more demanding industrial scenarios.

Chapter 8

Conclusions and future research proposals

8.1 Main achievements of the PhD Thesis

The primary objective of this thesis has been the development of a comprehensive technology capable of addressing robotic non-planar additive manufacturing (NPAM) from the design phase of parts to be manufactured, through to the implementation and validation of the methodology in a robotic NPAM station. These advancements are applicable to all polymer extrusion-based additive manufacturing techniques, as well as metal additive manufacturing technologies based on electron beam melting (EBM). This holistic breakthrough has been structured around three main contributions:

- **Methodology for Dual-Spatial transformation**

  The first major contribution is the establishment of a dual-space methodology operating between the *World space* and the *Slicing space*. This framework enables the transformation of conventional planar layers into curved layers suitable for non-planar manufacturing. By doing so, it resolves key challenges in adapting traditional slicing techniques to curved geometries, allowing for the realization of complex, highly customized structures with enhanced mechanical properties. This methodology ensures that the transition from design to fabrication is both seamless and efficient.

- **Robotic NPAM Station and Custom Slicer Development**

  The second contribution is the creation of a robotic NPAM station where the proposed methodology has been implemented and validated. Central to this system is a custom slicing tool capable of generating toolpaths aligned with the diverse specifications of non-planar manufacturing. This station has been designed to accommodate advanced configurations, such as multi-material deposition, ensuring flexibility and scalability for different applications. The combination of this hardware and software ecosystem enables a robust, automated workflow that bridges the gap between theoretical design and practical manufacturing.

- **Design Methodology for Complex Structures**

  The third contribution is a novel design methodology that integrates and leverages the two previous results. This approach facilitates the development of complex structures with diverse components by guiding the designer in exploiting the unique advantages of non-planar additive manufacturing. This framework not only enhances design creativity but also improves the functionality and structural integrity of the resulting parts.

These advancements have been validated through their application to the development of origami-inspired expandable skin structures within the framework of the BIOMET4D project. Additionally, four case studies in various fields have demonstrated the functionality of the proposed methodologies and their ability to address limitations inherent to conventional additive manufacturing processes.

In summary, the comprehensive framework developed in this thesis provides a unified solution for advancing NPAM technologies. By addressing design, manufacturing, and validation challenges, this work opens new possibilities for additive manufacturing in fields requiring geometrical complexity, enhanced mechanical performance, and material efficiency.

8.2 Conclusions on advances in Robot-based Non-planar Additive Manufacturing

From the perspective of an expert in Robotic Non-Planar Additive Manufacturing (RbNPAM), this thesis has successfully established a comprehensive and structured workflow for the real-world implementation of a robot-based non-planar additive manufacturing process. The methodology proposed in this research effectively integrates two distinct coordinate subspaces that are fundamental to the process: the World space, in which the manufactured part is physically realized, and the Slicing space, which governs the lamination strategy and trajectory generation. The transformation between these two spaces has been meticulously defined through mathematical mappings that enable the accurate conversion of standard Cartesian coordinate models into non-planar lamination paths, ensuring precise toolpath generation and material deposition.

A key contribution of this work is its successful integration into a robotic manufacturing cell, demonstrating the viability of multi-degree-of-freedom robotic systems for advanced additive manufacturing applications. To complement this experimental implementation, the research also introduces a custom-developed slicer equipped with a graphical user interface, which significantly enhances the usability of the proposed system. This slicer is designed to facilitate intuitive interaction with the slicing space, allowing users to visualize the non-planar slicing process and effectively configure deposition strategies. The graphical representation of toolpaths within the slicer provides users with a clear insight into the interaction between the Slicing space and the World space, which is critical for optimizing deposition accuracy, minimizing support material, and enhancing print quality.

Regarding the technical validation of the methodology, the precision of the robotic manipulator in executing the computed trajectories has been thoroughly evaluated. The system demonstrates a high degree of accuracy in following complex, non-planar paths, ensuring consistent layer deposition with minimal deviation. However, despite these achievements, a significant challenge remains in achieving a fully synchronized global architecture that seamlessly integrates the extruder, the robot's motion control, and the temperature regulation of both the heated bed and the extrusion nozzle. The absence of this synchronization currently limits the full automation potential of the system. Future work should focus on implementing a real-time feedback control system that dynamically adjusts extruder flow rates and robot kinematics in response to variations in print speed, material viscosity, and environmental conditions. Such an integration is essential for ensuring uniform layer adhesion, consistent extrusion rates, and the elimination of potential defects such as under-extrusion, over-extrusion, and thermal inconsistencies.

The slicer interface, as developed in this thesis, has demonstrated robust performance across a diverse set of test geometries, confirming its suitability for generalized use in non-planar additive manufacturing. However, an important limitation is that the current version of the slicer only supports the lamination of a single part at a time. This restriction imposes challenges for batch manufacturing, particularly in industrial settings where simultaneous production of multiple components is necessary for optimizing manufacturing throughput and reducing cycle times. Future enhancements should aim to introduce multi-part slicing capabilities, allowing for automated nesting and sequential trajectory planning for multiple objects within the same build volume.

Additionally, while the slicer successfully generates non-planar toolpaths, the output format remains a limiting factor for industrial deployment. The current implementation provides path data as discrete points, which must be further processed before execution. To align with standard robotic control frameworks, the system should be upgraded to generate directly interpretable output formats such as G-code or quaternion-based trajectory definitions. G-code compatibility would enable seamless integration with existing CNC-based and robotic additive manufacturing platforms, while quaternion-based representations would facilitate high-fidelity motion control and interpolation-free execution of non-planar trajectories. By incorporating these enhancements, the slicer would not only improve its operational efficiency but also expand its compatibility with a broader range of industrial robotic platforms.

In conclusion, while this thesis has made significant strides in demonstrating the feasibility of robot-based non-planar additive manufacturing, several key areas require further refinement to fully industrialize the process. The integration of a cohesive global control architecture, the advancement of the slicer's capabilities to support multi-part processing, and the implementation of industry-standard output formats are all crucial next steps.

8.3 Conclusions on advances in Design for Non-planar Additive Manufacturing

From the perspective of an expert in Design for Non-planar Additive Manufacturing (NPAM), this thesis successfully developed a methodology that significantly simplifies the design of complex patterns with specific curvatures. The method allows these curvatures to be seamlessly adapted to any surface through cubic splines, which provides great versatility to the approach. This flexibility is a key aspect of the design process, as it enables the creation of highly intricate and functional geometries that would otherwise be difficult or impossible to achieve using traditional design methods. The methodology's application to various case studies underscores its broad applicability and potential in diverse fields.

The thesis applied this design methodology to five distinct case studies, each highlighting a different aspect of NPAM's potential. The first, and most extensive, involved the development of a complete library of bimaterial origami actuators, utilizing degradation-based stimuli to generate skin expanders for the BIOMET4D project. This case study demonstrated the ability of NPAM to create highly adaptable and functional structures in the field of biomechanics, where the complex interactions between materials and their environments require precise, customized designs.It also demonstrates how DfNPAM enables the creation of 4D printing-based actuators capable of solving real-world problems.

In addition to the biomechanical applications, the thesis explored the creation of paths for printing a coronary stent, designed to be built on a non-planar support structure that also takes advantage of the developed methodology. This case study highlighted the capacity of NPAM to create biomedical devices that not only conform to complex geometries but also offer the possibility of optimizing the structural and functional characteristics of the final product. Similarly, in the field of soft robotics, the thesis demonstrated the creation of a bimaterial gripper combining rigid and flexible materials, showcasing the methodology's potential for designing functional robotic systems.

Further expanding the scope of the research, the thesis also applied the design methodology to map patterns on curved surfaces, particularly for tribological finishes on metals. This case study suggested the potential for automated trajectory generation for the deposition of chemical agents on a surface, highlighting how NPAM trajectories could enhance processes such as surface finishing. Finally, the thesis applied the methodology to the structural optimization of an aluminum sheet deep-drawing matrix made from polymeric material. This case study aimed to improve the structural rigidity, which is crucial in manufacturing processes, thereby demonstrating the methodology's relevance in optimizing industrial tooling and machinery.

Despite the success in developing these case studies, there remain areas for further investigation. One of the key goals for future research is to enhance the design software with an intuitive interface that simplifies the design process and directly connects to the slicer developed, creating a unified platform for NPAM. Such a development would streamline the workflow and make the methodology more accessible to practitioners. Another limitation to address in future research is the challenge of working with curves that are not of revolution, which would further extend the applicability of the methodology to more complex geometries. Additionally, the validation of the results would have been more robust if the first NPAM prototypes could have been printed using the designed robotic cell. This step would have provided critical insights into the practical application of the methodology in real-world manufacturing environments and helped to refine the overall process. Moving forward, these enhancements will be essential in advancing the practical use of NPAM in both research and industrial applications.

8.4 Future research proposals

The future lines of research derived from the conclusions of this thesis are organized into three main areas. The first line focuses on the validation of the process through the printing of the first prototypes using the robotic cell. To achieve this, the architecture of the cell needs to be finalized, including adjustments to temperature settings and extrusion speed. In addition, the synchronization of the different components—such as the robotic arm, extruder, and build platform—must be validated. Once these adjustments are made, the output results will need to be tested to ensure that the prototypes meet the required specifications. This step is crucial for ensuring that the robotic cell functions seamlessly and is capable of producing high-quality prints in real-world applications.

The second proposed avenue for future research involves further automating the generation of robotic manipulator trajectories through the use of more advanced mathematical tools. Specifically, the use of metric topological spaces is suggested. These spaces, more complex than $\{e\}$, ensure equidistance is preserved between points within the space. This enables meshing any surface in the $\{b\}$ space using equidistant points. Additionally, the implementation of higher-order splines is proposed to guarantee higher continuity conditions than those currently employed. This would allow the slicing space to be understood as a Riemannian manifold, simplifying the problem of maintaining equidistance between points. Some of this work has been already completed with the promising results on calculating equidistant points on curved surfaces as shown in Figures 8.1 and 8.2. Future implementations of triply–periodic minimal surfaces TPMS in curved layers could be developed by using the geodesic equidistant point distribution.

Aligned with this future direction, it is suggested to extend the generating curves by removing the axial symmetry condition. Using NURBS (Non-Uniform Rational B-Splines), the slicing space could be generalized to completely freeform surfaces, enabling the solid to be sliced perpendicularly to the layer-generating surface. This enhancement would significantly increase the versatility of the robotic cell. In this context, preliminary efforts have been initiated to convert geometries into non-axisymmetric curvature spaces, as illustrated in Figure 8.3. A cylindrical sector has been successfully mapped onto a space defined by a non-axisymmetric surface.

The third proposed direction for future research focuses on the development of advanced tools and methodologies for Design for Non-Planar Additive Manufacturing. By leveraging the parallel advancements in Robotic-based Non-Planar Additive Manufacturing, this research aims to expand the range of applications for this additive manufacturing technique. Specifically, it seeks to integrate and adapt materials and technologies already established for planar printing, such as multi-material printing, 4D printing, embedded sensors, degradable part supports, and shape memory alloys. In this research area, the automation of the generation of the axisymmetric build platform for a given loading case has been proposed. For instance, Figure 8.4 shows how the layers required to manufacture a racing car knuckle are optimized for its specific loading case by aligning the principal stresses with the favorable direction of the material's anisotropy.

Together, these three lines of future research will significantly enhance the capabilities of

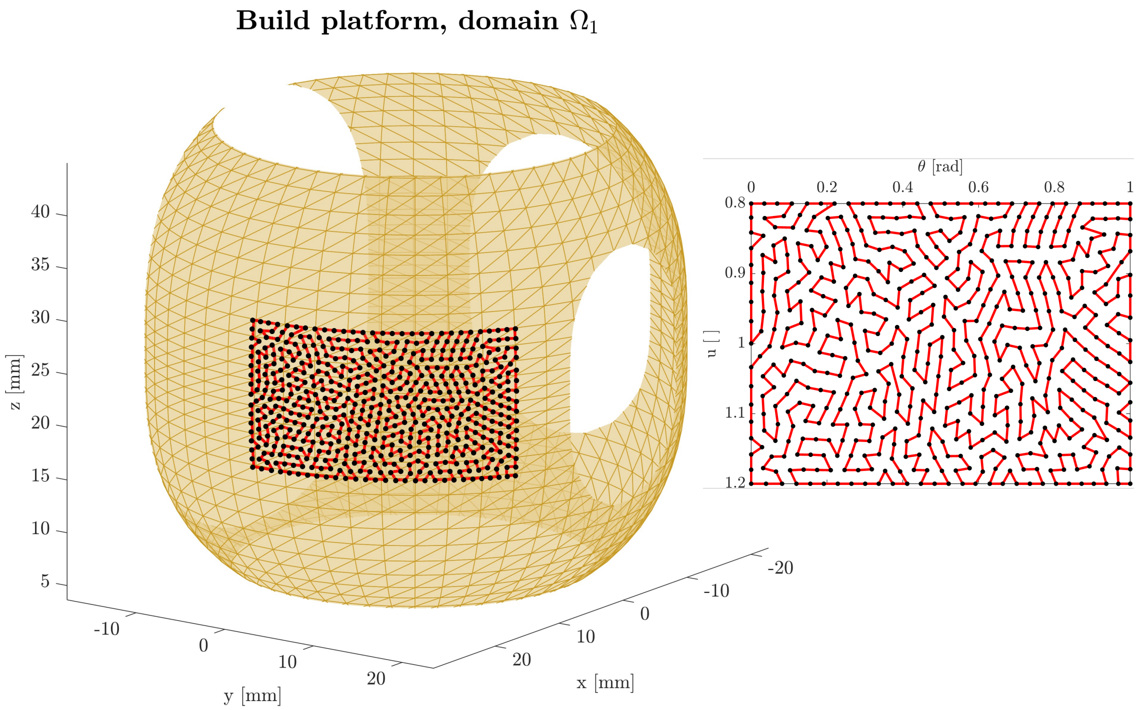
Build platform, domain Ω_1

Figure 8.1: Geodesically equidistant points in curved surfaces as base of TPMS in NPAM future implementation. Convex build platform.

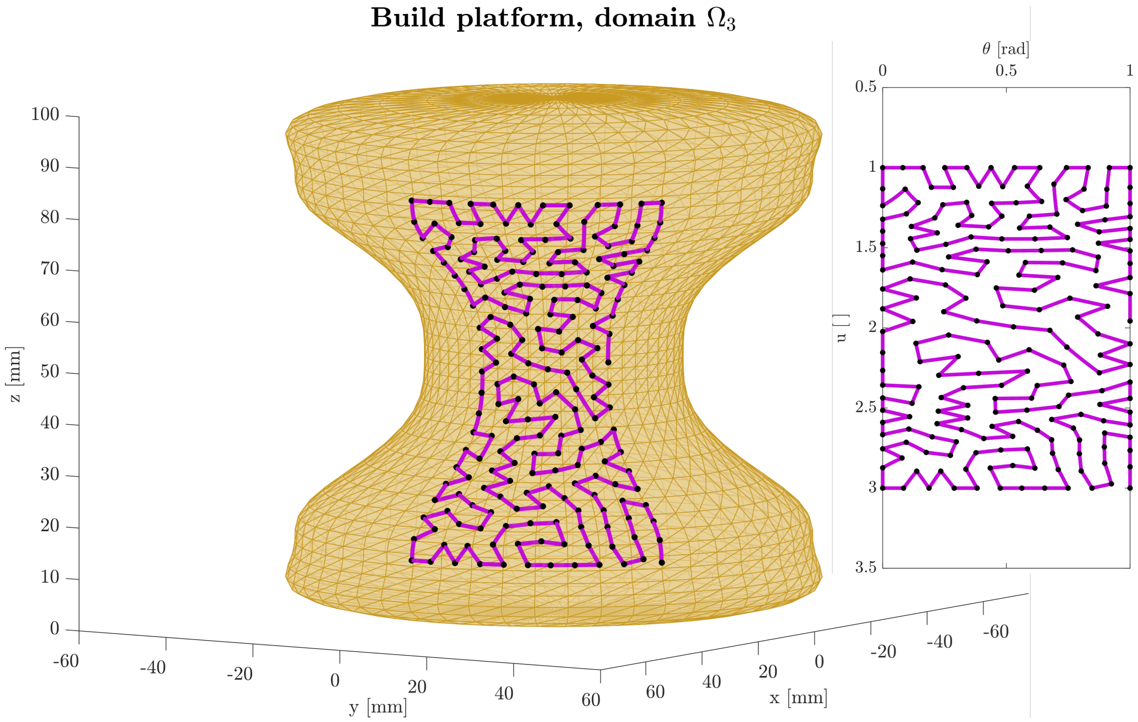
Build platform, domain Ω_3

Figure 8.2: Geodesically equidistant points in curved surfaces as base of TPMS in NPAM future implementation. Double curvature build platform.

robot-based non-planar additive manufacturing. The completion of the robotic cell and prototype validation will provide a critical foundation for real-world applications, while the software integration will streamline the design-to-manufacturing process. Expanding the lamination methodology to more complex surfaces will open up new possibilities for the creation of highly intricate, customized structures. These advancements will pave the way for broader industrial adoption of RbNPAM and establish it as a powerful tool for manufacturing a wide range of complex geometries.

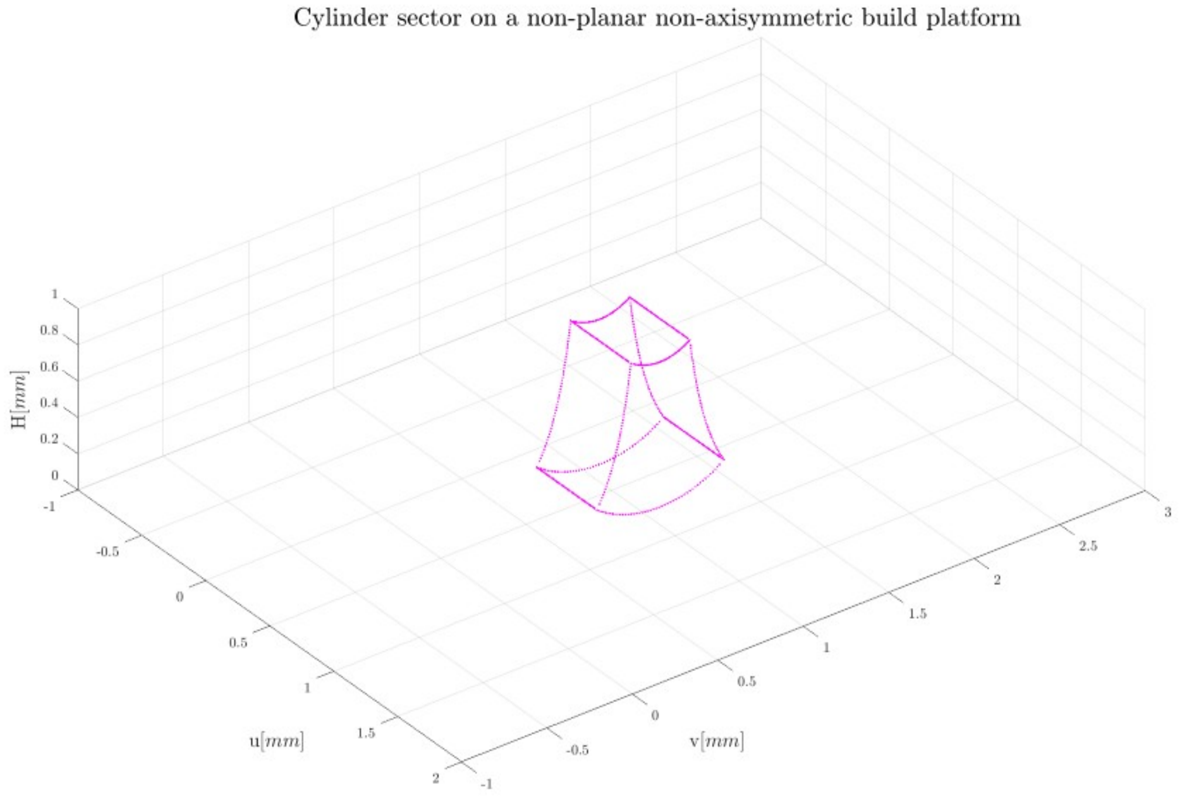

Figure 8.3: Cylindrical sector transformed into a space defined by a non-planar, non-axisymmetric base surface.

These prospective lines of research have been concretely translated into action through a competitive research project awarded to the Polytechnic University of Madrid (UPM) under the framework of a public-private collaboration call. This initiative is specifically aimed at applying the developed engineering methodology to the re-additivation of polymeric molds, which are extensively used in the lamination process of carbon fiber components. The project has secured a funding allocation of €300,000 for UPM, thereby laying a solid foundation for the implementation and consolidation of the proposed research directions over the next few years.

This financial support will contribute to the continued advancement of the robotic manufacturing cell, foster the seamless integration of the necessary software tools, and promote

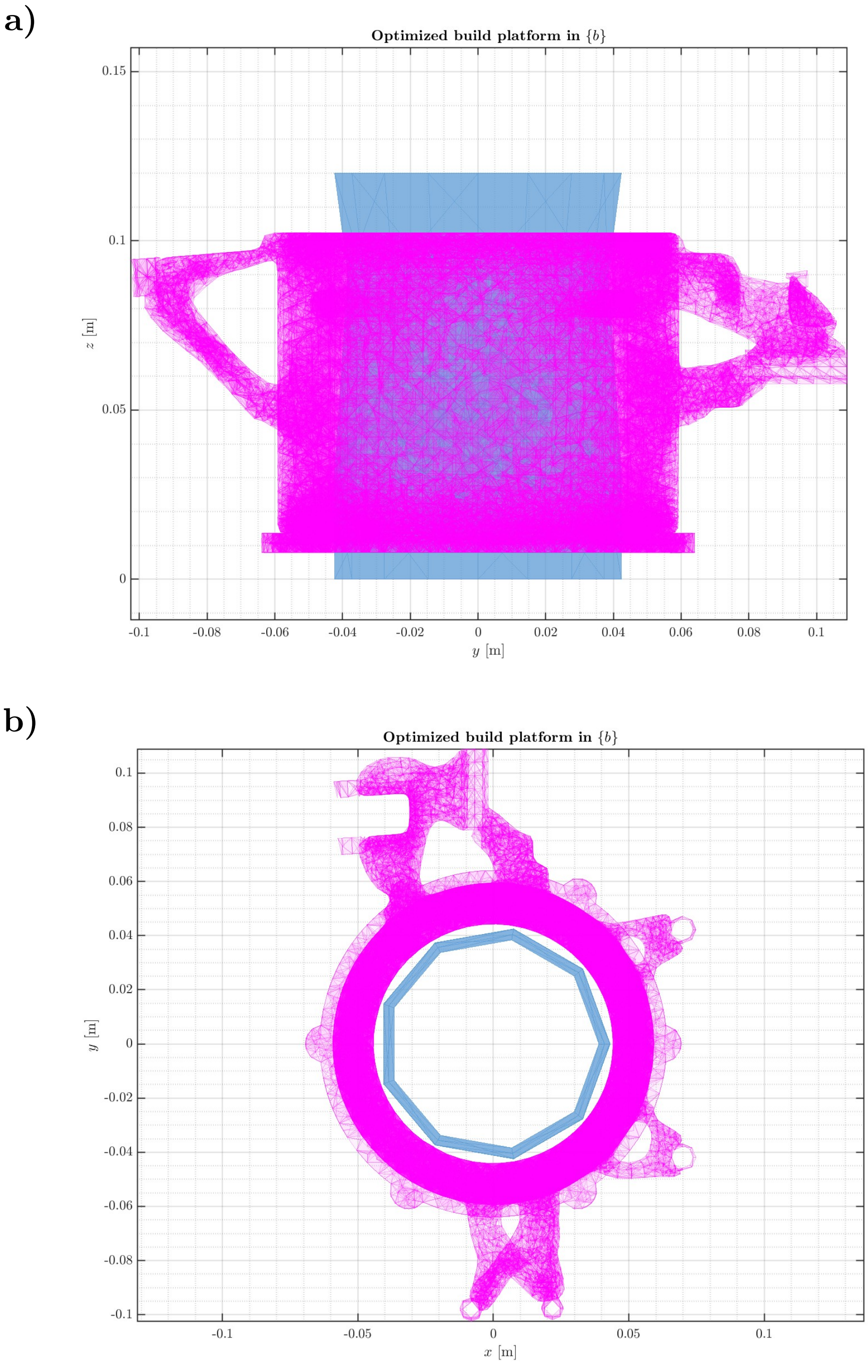

Figure 8.4: Optimization process for the racing car knuckle build platform. The layers are constructed by offsetting the build platform and aligned with the principal stresses in the material's preferred direction of anisotropy for the specific load case.

the refinement and broader application of the lamination methodology. As a result, the developed methodology will be positioned for practical deployment within advanced manufacturing scenarios involving carbon fiber composites, further solidifying the role of robot-based

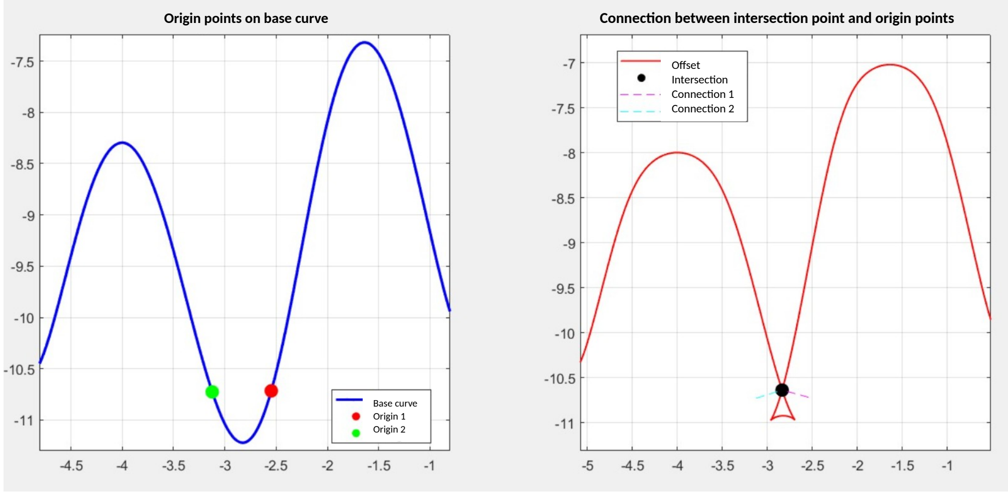

Figure 8.5: Automated identification of non-bijective regions through offset curve intersections.

non-planar additive manufacturing (RbNPAM) in industrial settings. Moreover, the project has already started delivering preliminary outcomes, particularly through a dedicated work package focused on the automated identification of bijectivity zones in non-axisymmetric curves. This directly addresses and begins to automate the resolution of the bijectivity problem described throughout this doctoral thesis. The process of detecting bijectivity areas is illustrated in Figure 8.5.

8.5 Environmental, social, and economic impact of the PhD Thesis

The research on robot-based non-planar additive manufacturing presents significant economic, environmental, and social benefits, particularly in the context of sustainable industrial development and healthcare innovation. From an economic standpoint, NPAM enhances manufacturing efficiency by reducing material waste, optimizing production times, and enabling the fabrication of complex geometries with minimal post-processing. This directly aligns with Sustainable Development Goal 9 **(SDG 9)** (Industry, Innovation, and Infrastructure) by fostering technological advancements in manufacturing and improving productivity in key sectors such as aerospace, automotive, and biomedical industries. The ability to produce high-strength, lightweight components using additive techniques reduces reliance on expensive subtractive manufacturing processes, lowering operational costs and promoting economic competitiveness [222].

From an environmental perspective, NPAM significantly contributes to **SDG 12** (Responsible Consumption and Production) by optimizing material utilization and minimizing waste generation. Traditional subtractive manufacturing methods often result in high material wastage, whereas additive manufacturing deposits material only where necessary. Furthermore, NPAM supports circular economy principles by integrating recycled materials into production, reducing dependency on virgin resources. Research in biodegradable and bio-based feedstocks for additive manufacturing further aligns with **SDG 13** (Climate Action) by reducing carbon emissions associated with conventional polymer and metal manufacturing processes.

The integration of robotic systems in NPAM also enhances energy efficiency, directly supporting **SDG 7** (Affordable and Clean Energy). Compared to conventional additive manufacturing (AM) processes, NPAM's ability to print non-planar structures reduces the need for excessive support structures, leading to lower energy consumption per unit of manufactured material. This is particularly relevant in aerospace and automotive applications, where lightweight structures directly impact fuel efficiency, contributing to lower overall environmental footprints.

One of the most notable contributions of NPAM is its impact on healthcare, particularly in the development of customized medical devices, including biodegradable coronary stents and origami-based robotic grippers for medical applications. The ability to fabricate patient-specific implants aligns with **SDG 3** (Good Health and Well-being) by improving treatment outcomes, reducing surgery preparation times, and enhancing patient recovery. The research supports the development of bioresorbable implants, reducing the need for secondary surgeries to remove devices, which in turn lowers healthcare costs and improves patient quality of life.

Additionally, NPAM contributes to regenerative medicine and prosthetics by enabling the design of advanced biomimetic structures that better integrate with human tissues. The use of functionally graded materials in NPAM-based implants improves mechanical compatibility with biological structures, reducing risks such as implant rejection or failure. These advancements enhance access to high-quality medical solutions while promoting the use of biocompatible materials, further reinforcing sustainability in healthcare manufacturing.

In conclusion, the adoption of NPAM presents a paradigm shift in industrial and medical manufacturing, offering a pathway toward economic efficiency, environmental sustainability, and medical innovation. By addressing key challenges related to energy consumption, material waste, and personalized healthcare solutions, this research aligns with global sustainability goals, promoting innovation-driven economic growth while mitigating environmental impact. The ability to fabricate customized medical devices, improve energy efficiency, and support a circular economy underscores NPAM's potential to redefine manufacturing across multiple industries while contributing to a more sustainable and healthier future.

8.6 Summary of the scientific-technological contribution of the PhD Thesis

Articles in scientific journals

- Adrián López-Arrabal, Álvaro Guzmán-Bautista, William Solórzano-Requejo, Francisco Franco-Martínez, Mónica Villaverde, Axisymmetric non-planar slicing and path planning strategy for robot-based additive manufacturing, Materials & Design, Volume 241, 2024, 112915, ISSN 0264-1275, https://doi.org/10.1016/j.matdes.2024.112915

Publications in proceedings of scientific conferences

- Adrián López-Arrabal, Álvaro Guzmán-Bautista, William Solórzano-Requejo, Amparo Sancho-Arellano, Francisco Franco-Martínez, Andrés Díaz Lantada, Path planning design for robot based non-planar additive manufacturing case study: coronary stent, 9th International Conference on Mechanical Engineering and Robotics Research (ICMERR), DOI: 10.1109/ICMERR64601.2025.10949923.
- Laura Gil Villacastín, Álvaro Guzmán-Bautista, Adrián López Arrabal, Enrique Chacón-Tanarro, Amparo Sancho-Arellano, Miguel Lerín-Alonso, Design for Robot-Based Non-Planar Additive Manufacturing Case Study: Soft Robotics Gripper, 9th International Conference on Mechanical Engineering and Robotics Research (ICMERR), DOI: 10.1109/ICMERR64601.2025.10949917.
- Álvaro Guzmán-Bautista, Laura Gil Villacastín, Adrián López Arrabal, Enrique Chacón-Tanarro, Juan Manuel Muñoz-Guijosa, Antonio Vizán-Idoipe, Automatic State Space-based Dynamic Characterization of Industrial Machining Robots, 9th International Conference on Mechanical Engineering and Robotics Research (ICMERR), DOI: 10.1109/ICMERR64601.2025.10949941.
- Álvaro Guzmán-Bautista, Adrián López Arrabal, Enrique Chacón-Tanarro, Beatriz Pérez-Hickman las Matas, Metodología de calibración de estación de mecanizado robótico basada en flujo de trabajo CNC, 23^{er} Congreso Nacional de Ingeniería Mecánica, Anales de la Ingeniería Mecánica, Vol 1, 2023, p 149, ISSN: 0212-5072, http://www.asoc-aeim.es/anales.html

Final degree theses supervised

- Co-direction with Prof. Miguel Clavijo Jiménez of the Bachelor's Thesis of Mr. Mario García Martínez, Caracterización de la incertidumbre cinemática de robot colaborativo por propagación de error en las articulaciones, 2023.
- Co-direction with Prof. Álvaro Guzmán Bautista of the Bachelor's Thesis of Mr. Alejandro Franco Gutiérrez, Diseño de metodología de laminado de sólidos 3D para generación de trayectorias no planas en fabricación aditiva robótica, 2023.
- Co-direction with Prof. Álvaro Guzmán Bautista of the Master's Thesis of Ms. Amparo Sancho Arellano, Generación y validación de trayectorias no planares para fabricación

aditiva robotizada, 2023.

- Co-direction with Prof. Juan Manuel Muñoz Guijosa of the Bachelor's Thesis of Ms. Laura Gil Villacastín, Metodología automatizada para la caracterización del comportamiento dinámico de un brazo robot ante vibración libre, 2023.
- Co-direction with Prof. Francisco Franco Martínez of the Bachelor's Thesis of Mr. Víctor Bueno Ruano, Desarrollo de interfaz gráfica y algoritmos de relleno para slicer de fabricación aditiva no plana, 2024.
- Co-direction with Prof. Andrés Díaz Lantada of the Master's Thesis of Ms. Victoria Gonçalves da Corte, Diseño para impresión 4D de patrones origami activados por degradación, 2024.
- Co-direction with Prof. Andrés Díaz Lantada of the Bachelor's Thesis of Mr. José Ramón Tiemblo Martín-Calderín, Diseño de actuadores basados en origami para fabricación aditiva robótica no plana, 2024.
- Co-direction with Prof. Juan Manuel Muñoz Guijosa of the Master's Thesis of Ms. Laura Gil Villacastín, Caracterización dinámica automatizada de manipuladores robóticos basada en espacio de estados para mecanizado, 2024.
- Co-direction with Prof. Enrique Chacón Tanarro of the Bachelor's Thesis of Mr. Rubén Peña Pulido, Caracterización de las juntas de un brazo robótico colaborativo mediante ensayos de fricción viscosa y rigidez, 2024.
- Co-direction with Prof. Enrique Chacón Tanarro of the Master's Thesis of Mr. Andrés Jaldo Serrano, Validación del conformado de chapa metálica mediante el uso de matricería Impresa en 3D, 2024.
- Co-direction with Prof. Enrique Chacón Tanarro and Prof. Álvaro Guzmán Bautista of the Bachelor's Thesis of Mr. Adrián Martínez García, Diseño y fabricación de cabezal de extrusión para estación robotizada de fabricación aditiva no plana, 2024.

Research projects

- Predicción automatizada del comportamiento dinámico de un brazo robot para corrección de trayectorias en la realización de tareas de alta precisión (ETSII-UPM24-PU02). Primeros proyectos ETSII-UPM 2024, PI: Adrián López Arrabal.
- Calibración de posicionamiento absoluta de un robot por reconocimiento de patrones geométricos mediante algoritmos de resolución del problema de máximo clique (ETSII-UPM24-PM02). Primeros proyectos ETSII-UPM 2024, participation as research team member. PI: Álvaro Guzmán Bautista
- BIOMET4D: Smart 4D biodegradable metallic shape-shifting implants for dynamic tissue restoration. International, Horizon Europe, Participation as research team member. Project coordinator: Jennifer Patterson, IMDEA Materials Institute. UPM's PI: Andrés Díaz Lantada
- CYBERCELL: Sistema de producción ciberfísico para la planificación inteligente de

células de fabricación (PID2021-124838OB-I00). Nacional, Plan estatal, 2022-2025, Participation as research team member. PIs: José Ríos Chueco, and Enrique Chacón Tanarro.

8.7 Educational contribution of the PhD Thesis

In the educational field, efforts have been made to ensure that the thesis has a real impact on improving the quality of teaching in the degree programs offered at the ETSI Industriales of the Universidad Politécnica de Madrid. Along these lines, the methodology developed in the thesis has been implemented in the course "Ingenia" of the Master's in Industrial Engineering first course, a project-based learning (PBL) course in which students acquire cross-disciplinary skills through the completion of scientific and technological projects.

Under the title *"Ingenia: Advanced Manufacturing Systems,"* the aim is for students to apply the developed methodology for non-planar additive manufacturing of parts. In addition, they can explore areas such as improving the existing robotic architecture, software, and hardware, and even implement these enhancements in a real environment using a collaborative robot. Throughout this process, they develop skills such as communication, teamwork, interpersonal relationships, time management, initiative, and creative thinking in a setting that simulates a professional environment.

The course is conducted annually in collaboration between the Department of Mechanical Engineering and the Department of Industrial Management, involving 7 professors and a total commitment of 12 ECTS credits. It was successfully carried out during the 2023-2024 academic year and is currently being taught in the 2024-2025 academic year.

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Annex A: Slicer validations through simple geometries

This appendix presents a total of four case studies used to validate the correct operation of the developed slicer.

Half cylinder on a cylindrical built platform:

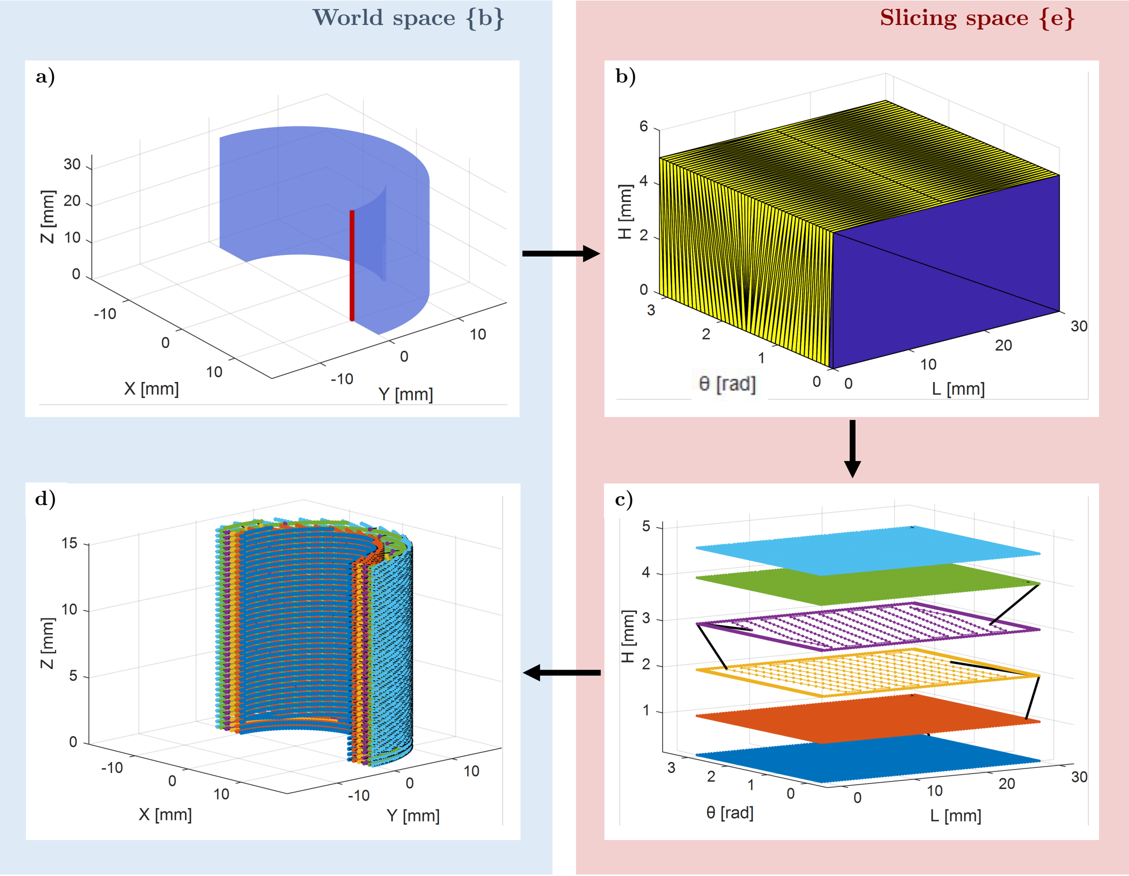

Figure 6: Trajectory generation for half of a cylinder using cylindrical layers. a) STL file and print bed in World space referred to $\{b\}$. b) STL file converted to Slicing space referred to $\{e\}$. c) laminated solid in $\{e\}$ with its defined trajectories: $\mathcal{X}_{\{e\}}$. d) laminated solid in $\{b\}$ with its defined trajectories: $\mathbf{X}_{\{b\}}$. Normal vectors in black represents the extruder orientation.

First, Figure 6 illustrates the slicing of a half-cylinder on a cylindrical layer, seen in figure 6.a. Figure 6.c shows how the walls of the layers are defined, their direction based on the guiding vector, and the two upper and lower layers that, together with the walls, form the shell of the part. Finally, in Figure 6.d can be seen the final result of the overall process.

In Figure 7, the previous result will be shown layer by layer in both spaces, allowing a detailed observation of the point density and the orientation of the normal vectors.

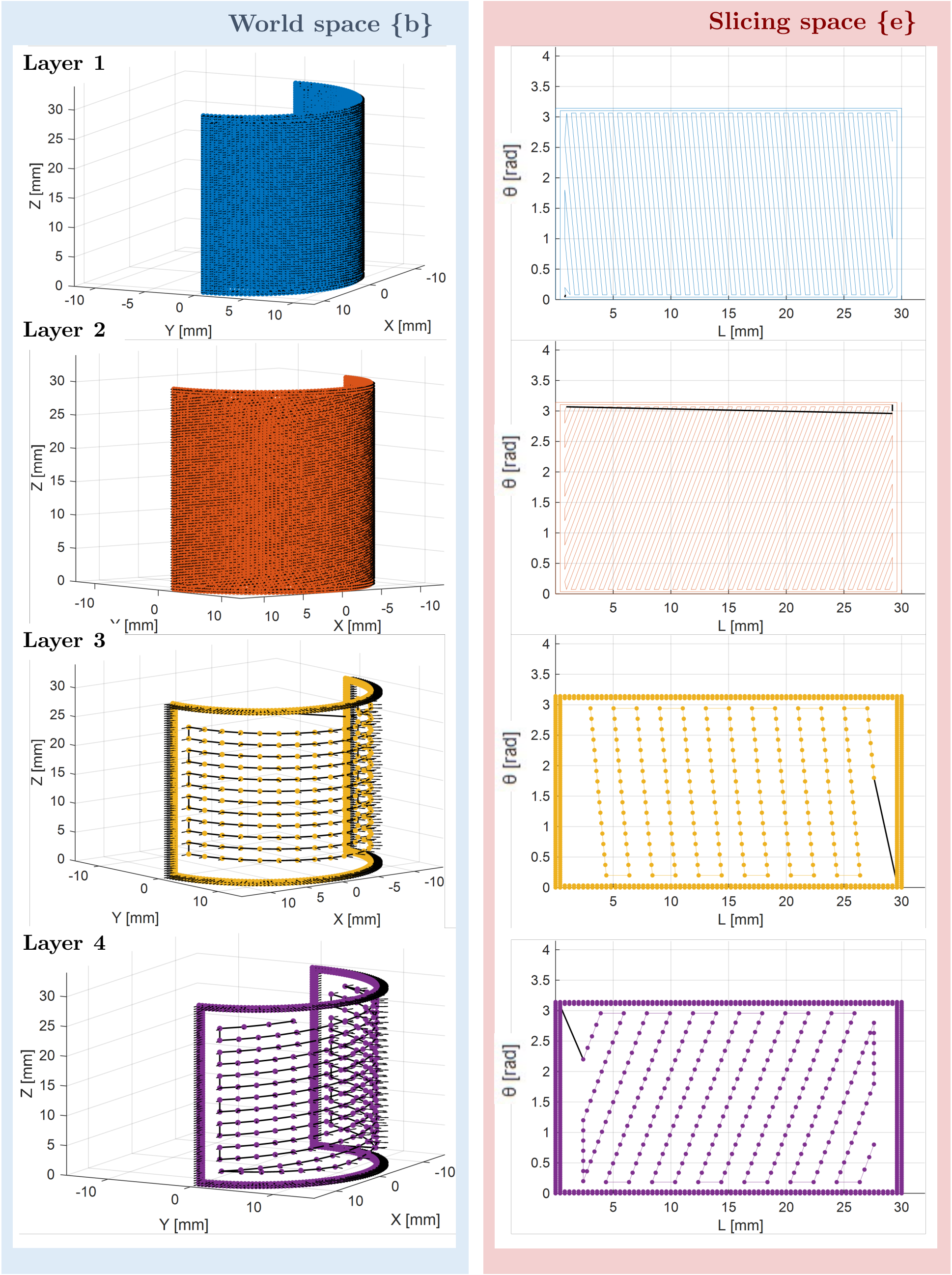

Figure 7: First four layers of the half cylinder on a cylindrical build plate case. Layers 1 and 2 with 100% infill built on perpendicular directions and layers 3 and 4 with 20% infill also built in perpendicular directions.

Cylinder on a cylindrical built platform:

Figure 8 illustrates the slicing of a cylinder on a cylindrical layer, seen in figure 8.a. Figure 8.c shows how the walls of the layers are defined, their direction based on the guiding vector, and the two upper and lower layers that, together with the walls, form the shell of the part. Also it has been checked the correct generation of the sewed wall Finally, in Figure 8.d can be seen the final result of the overall process.

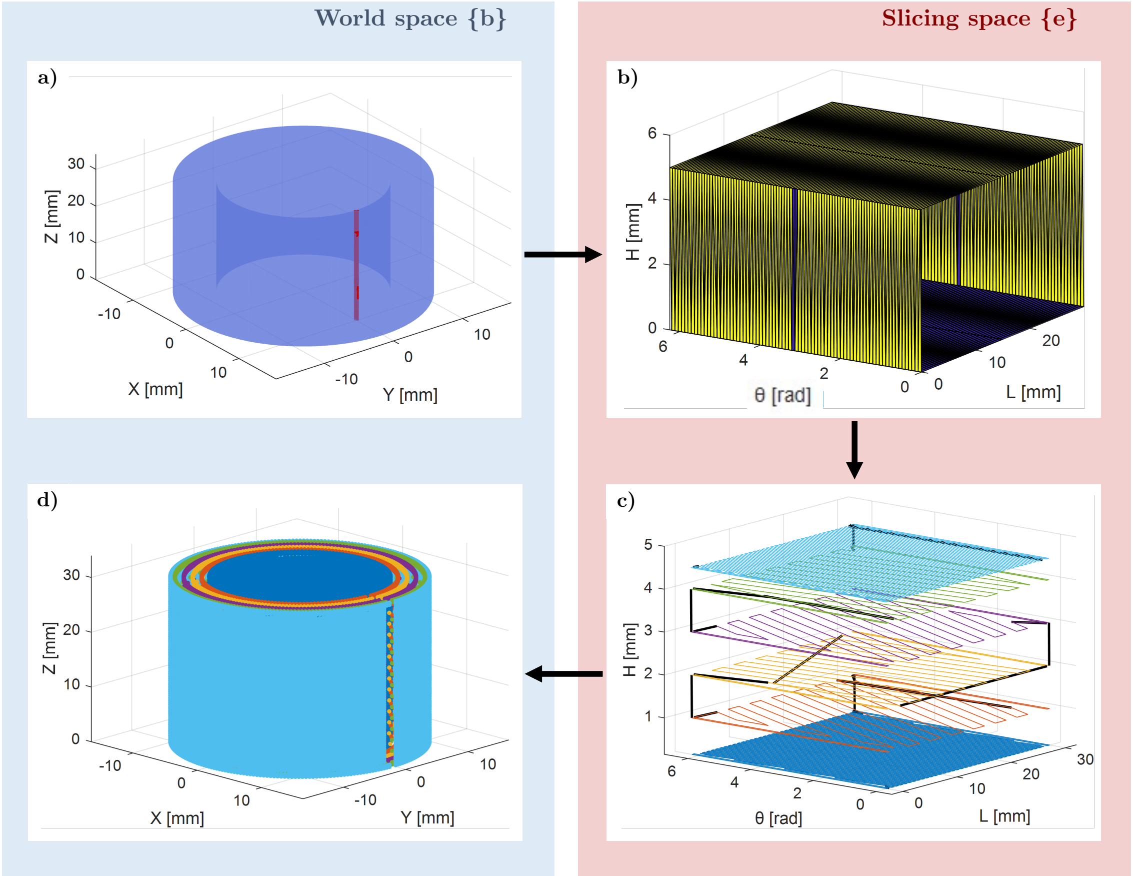

Figure 8: Trajectory generation for a cylinder using cylindrical layers. a) STL file and print bed in World space referred to $\{b\}$. b) STL file converted to Slicing space referred to $\{e\}$. c) laminated solid in $\{e\}$ with its defined trajectories: $\mathcal{X}_{\{e\}}$. d) laminated solid in $\{b\}$ with its defined trajectories: $\mathbf{X}_{\{b\}}$. Normal vectors in black represents the extruder orientation.

Truncated cone on a conical built platform:

Figure 9 illustrates the slicing of a truncated cone on a conical layer, seen in figure 9.a. Figure 9.c shows how the walls of the layers are defined, their direction based on the guiding vector. No upper or lower 100% infill layers have been included to check the infill performance. Also it has been checked the correct generation of the sewed wall Finally, in Figure 9.d can be seen the final result of the overall process. It is also validated in this case study that the interpolation of points in trajectories with bigger radius include more density than the ones with a lower radius to avoid chordal error.

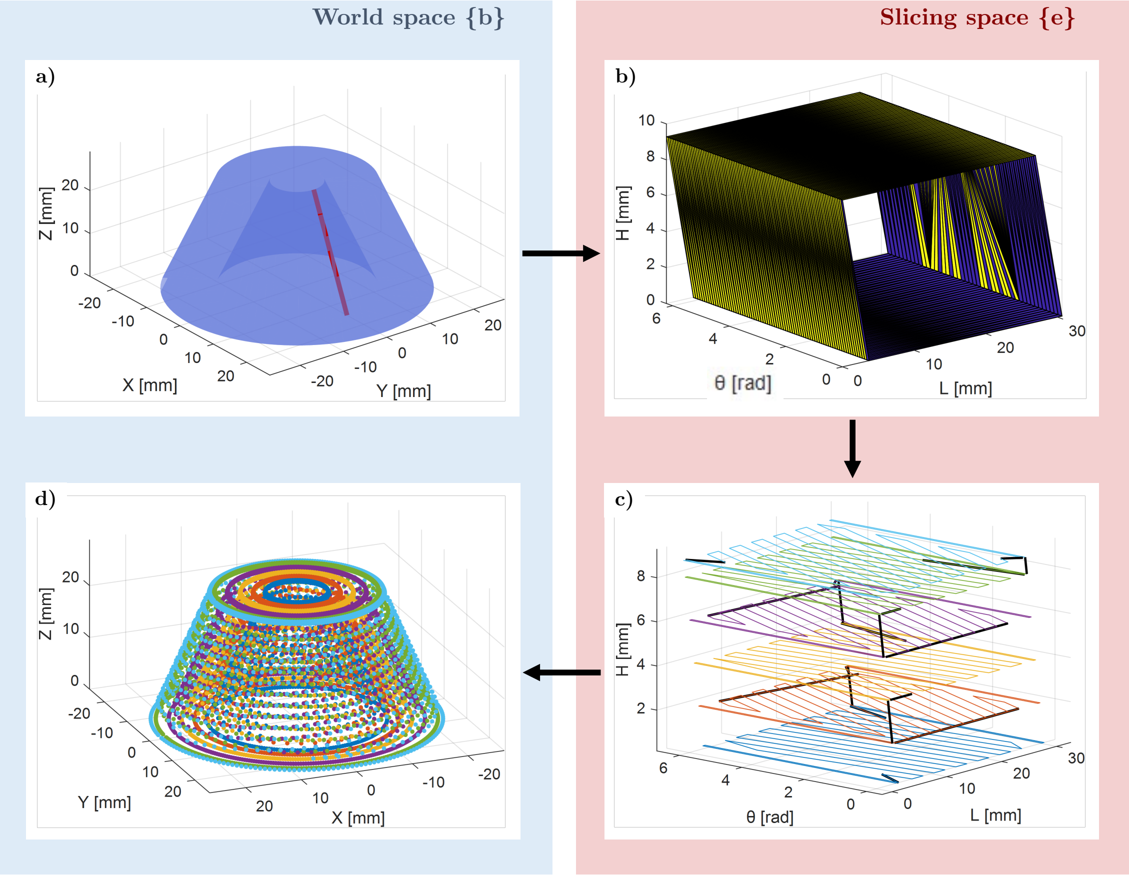

Figure 9: Trajectory generation for a truncated cone using conical layers. a) STL file and print bed in World space referred to $\{b\}$. b) STL file converted to Slicing space referred to $\{e\}$. c) laminated solid in $\{e\}$ with its defined trajectories: $\mathcal{X}_{\{e\}}$. d) laminated solid in $\{b\}$ with its defined trajectories: $\mathbf{X}_{\{b\}}$. Normal vectors in black represents the extruder orientation.

Hourglass figure on an hourglass-shape built platform:

Finally, double curvature surfaces have been tested to validate the slicer. Figure 10 illustrates the slicing of half hourglass shaped model sliced with a hourglass-shape layers, seen in figure 10.a. Figure 10.c shows how, in this case, one wall has been defined and the infill direction based on the guiding vector. No upper or lower 100% infill layers have been included to check the infill performance. Finally, in Figure 10.d can be seen the final result of the overall process. It is also validated in this case study that the interpolation of points in trajectories with bigger radius include more density than the ones with a lower radius to avoid chordal error.

After testing the algorithm on complex curvature cases, the next step is to validate its performance on non-revolution shapes. To achieve this, a cube was sliced on an hourglass-shaped bed. The results are displayed in Figure 11. This figure confirms that, for any given geometry, a curved bed can be identified to optimize its mechanical properties in a specific direction or enhance its surface finish. This is achieved without the need for the geometry to be a surface of revolution.

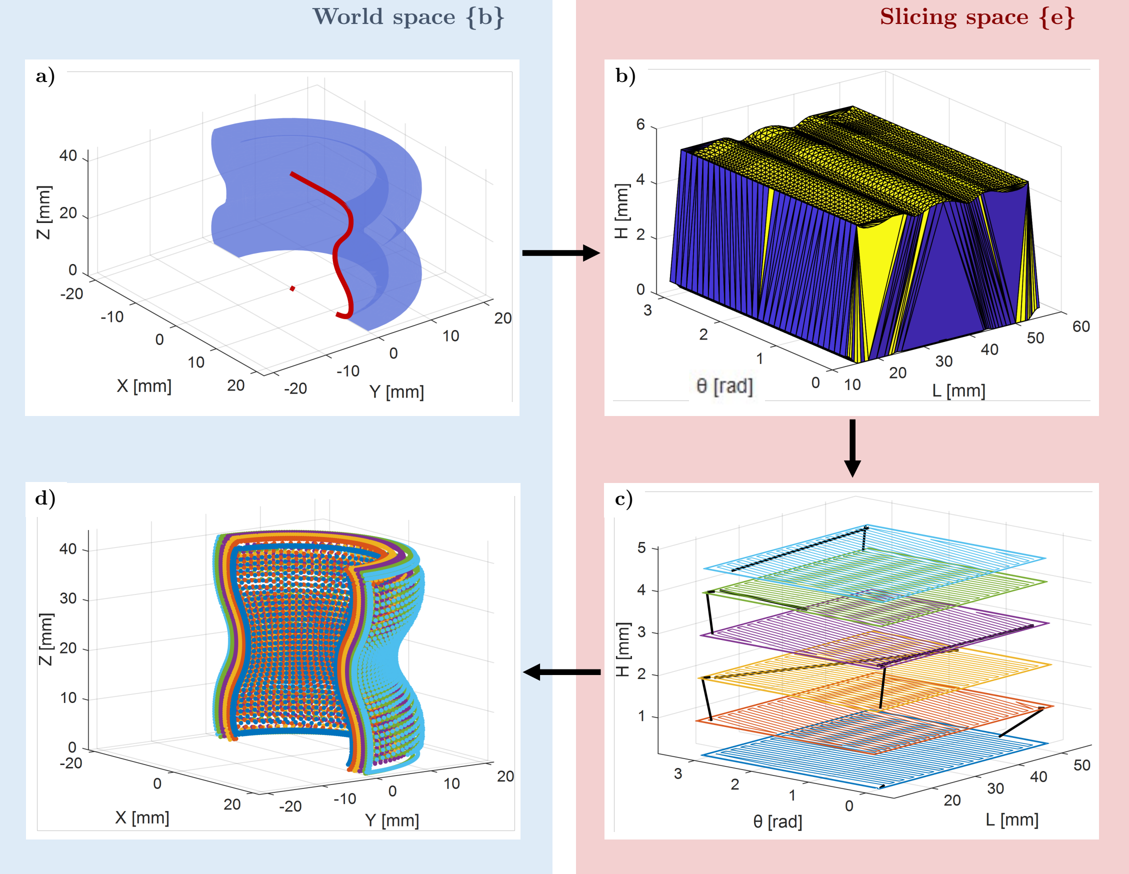

Figure 10: Trajectory generation for half hourglass shaped model sliced with a hourglass-shape layers. a) STL file and print bed in World space referred to $\{b\}$. b) STL file converted to Slicing space referred to $\{e\}$. c) laminated solid in $\{e\}$ with its defined trajectories: $\mathcal{X}_{\{e\}}$. d) laminated solid in $\{b\}$ with its defined trajectories: $\mathbf{X}_{\{b\}}$. Normal vectors in black represents the extruder orientation.

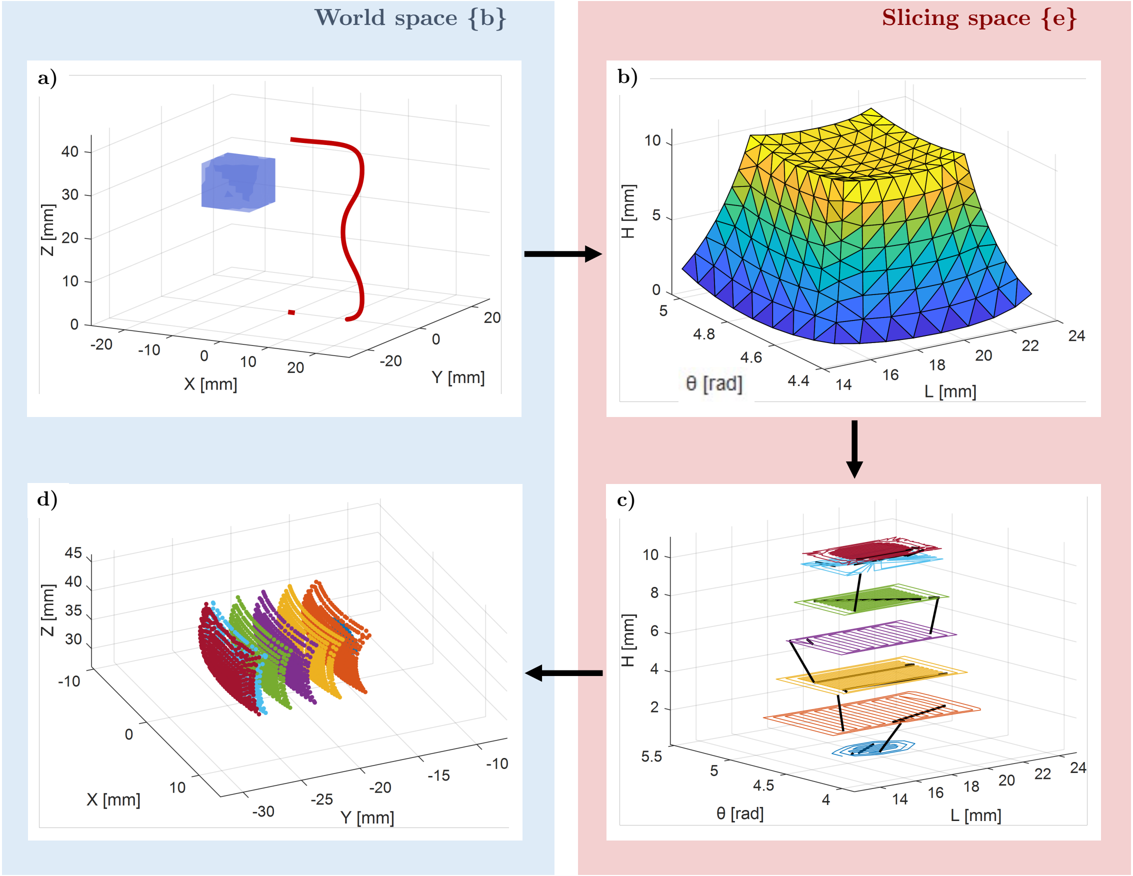

Figure 11: Trajectory generation for a cube model sliced with a hourglass-shape layers. a) STL file and print bed in World space referred to $\{b\}$. b) STL file converted to Slicing space referred to $\{e\}$. c) laminated solid in $\{e\}$ with its defined trajectories: $\mathcal{X}_{\{e\}}$. d) laminated solid in $\{b\}$ with its defined trajectories: $\mathbf{X}_{\{b\}}$. Normal vectors in black represents the extruder orientation.