# Automatic planning strategy for robotic lay-up of prepregs on a complex-shaped mold

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**Keywords:** Robotic Layup, Composites Manufacturing, Prepreg Forming, Process Planning

**Abstract.** The evolution of composite component production has been driven by a constant quest for improvements in process efficiency, precision, and repeatability. The eventual transition from traditional hand layup to robotic layup represents a significant step in this evolution. The implementation of robotic layup systems has become increasingly prevalent in the manufacturing industry, particularly in the aerospace and automotive sectors, where lightweight, strength, and precision are mandatory requirements. Ideally, the goal is the development of processes where a highly precise robotic arm could automate the deposition of composite materials onto the mold, providing a certain reduction of human errors, and minimizing material waste and associated costs. In this context, this paper proposes a computational tool that is able to provide automatic layup planning for the robotic layup process. The implemented algorithm incorporates the knowledge of a professional laminator: it can automatically analyze a generic mold surface of complex shape, work out the correct strategies for lamination, and generate instructions for robot movements.

## Introduction

In the ever-evolving landscape of advanced manufacturing, the aerospace and automotive industries are continually pushing the boundaries of materials and design to enhance performance and efficiency [1]. In this framework, advanced process monitoring, control and prediction is fundamental for the realization of robust manufacturing of high-performances components [2-4]. One main aspect of this evolution is the integration of automated programming for the robotic layup of prepreg onto complex mold shapes [5]. Prepreg, a composite material consisting of reinforcing fibers pre-impregnated with a resin matrix, offers exceptional strength-to-weight ratios, making it a preferred choice for high-performance applications [6,7]. The utilization of robotics in the layup process brings forth unprecedented precision, repeatability, and efficiency, ultimately revolutionizing the way composite structures are manufactured [8].

Manual layup is often labor-intensive, time-consuming, and error-prone, making it a bottleneck in producing these high-performance materials [9]. Robotic layup emerges as a promising solution to overcome these drawbacks and enhance the efficiency and quality of the layup process.

Robotic layup involves the automated placement of prepreg plies onto a mold surface according to a predefined layup sequence. This process requires precise control of the robot's toolpath and the ability to handle the delicate prepreg materials without damage [10]. Automated programming plays a crucial role in enabling robotic layup, as it transforms the layup sequence into a series of instructions that the robot can execute [8].

The automation of the layup process not only addresses the challenges posed by intricate mold shapes but also significantly reduces human error, resulting in consistently high-quality composite structures [11]. Through the integration of advanced algorithms and robotic systems, manufacturers can achieve unparalleled accuracy in the placement of prepreg layers, optimizing

Materials Research Proceedings 41 (2024) 558-567 https://doi.org/10.21741/9781644903131-62

the mechanical properties of the final composite part [12,13]. Automated robotic layup offers several advantages over manual layup, including:

- increased efficiency: robots can layup prepreg at a much faster rate than humans, reducing production time and cost;
- improved accuracy: robots can precisely place prepreg plies with minimal error, ensuring the manufactured part's consistent quality and dimensional accuracy[14];
- reduced labor costs: By automating the layup process, manufacturers can reduce reliance on skilled labor and associated costs;
- improved worker safety: manual layup can be hazardous due to the handling of sharp prepreg materials and the exposure to fumes and solvents. Robots can perform layup tasks safely without exposing workers to these risks.

The use of automated programming for robotic layup has the potential to revolutionize the manufacturing of carbon fiber composites. By automating this critical step, manufacturers can achieve significant improvements in efficiency, accuracy, and cost-effectiveness, paving the way for the widespread adoption of these high-performance materials in various applications [13-15].

The idea behind this work is the creation of a tool to improve the efficiency of the robotic layup process and reduce human involvement even in the coding phase, simply providing the discretized surface of the mold as input for the algorithm, in charge of the definition of the layup strategy. This step is supported by a forming simulation, where prepregs are modelled as a virtual grid in which cell edges represent the fiber yarns, and the cell nodes represent their crossing points.

## Materials and methods

The tool mentioned above has been implemented in MATLAB environment. The algorithm starts by importing the STL file of the mold surface to be processed. "Gmsh", an open-source CAE software widely used for FEM analysis, has been used for mesh generation.

Several surface geometries have been created to test the algorithm under different conditions. CADs of the molds have been made with CATIA V5 software and then loaded into the MATLAB environment.

The implemented algorithm starts by loading the discretized surface of a mold. In order to understand the geometry loaded by the user, the algorithm first needs to process the mesh and its elements. After that, following a series of iterations, the choice of the best drafting strategy is provided. The best strategy is defined in terms of the order of areas of the surface to be processed during the robotic layup process in order to incur as little deformation of the prepreg as possible. In fig. 1, a description of the implemented algorithm is provided via flowchart describing its main steps.

After loading the discretized surface, the first calculation performed is to identify the normal vectors for each mesh element. The surface is divided into sub-surfaces, and the curvature for each sub-surface is estimated using a Gaussian curvature calculation function. Next, the user is prompted to specify which part of the surface will be involved in the layup process. The user has the option to choose whether to lay up the entire mold surface or only a portion of it. These steps aim to reduce the amount of data as the algorithm progresses. Once the user selects the sub-surfaces to be processed, a new discretized surface is created, consisting only of the parts involved in the layup process.

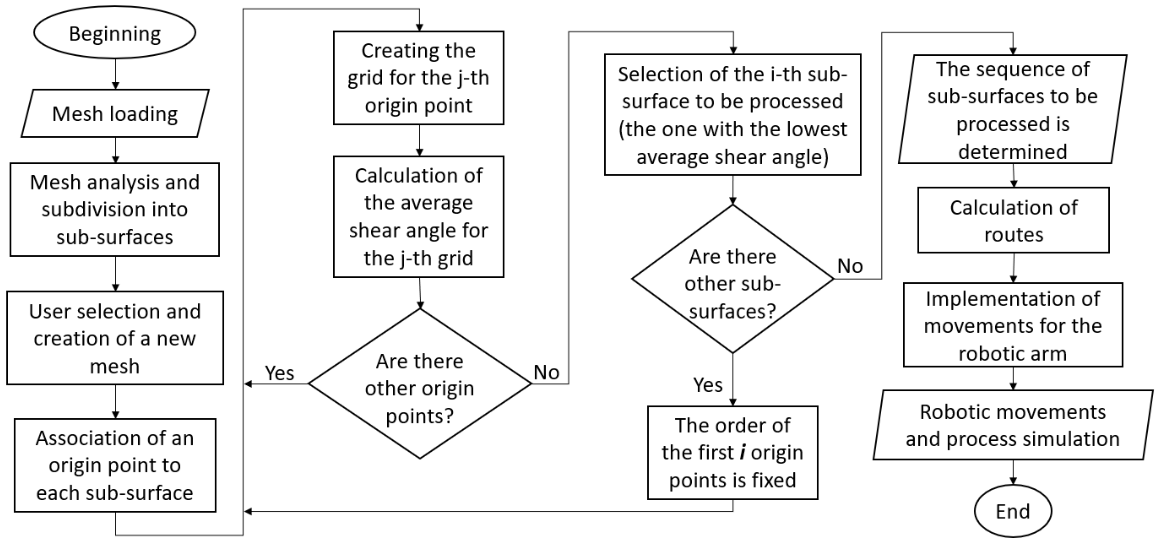


*Figure 1 - Description of the implemented algorithm using a flowchart describing its main steps.*

From this point on, the algorithm incorporates concepts from another work described in the article "A simple MATLAB draping code for fiber-reinforced composites with application to optimization of manufacturing process parameters" [16]. The processes outlined in this article are implemented to provide data better suited for the automatic programming of a robotic layup process.

For this new surface, a layup simulation is performed. The prepreg is simulated by creating a grid on the surface mold from a specific starting point (see Fig. 2). The choice of the starting point is crucial as it represents the initial contact between the prepreg sheet and the mold during the actual layup. The simulation yields different results for different starting points, mirroring the real process where the first point of contact influences the entire lay-up outcome. The curvatures encountered during layup deform the prepreg based on the starting point and layup directions.

The objective is to simulate layup from various points, studying the deformation of the virtual prepreg sheet, and defining the optimal layup approach that results in the best layup strategy for the specific mold surface to be machined. Finally, all information generated in the previous steps is collected and provided to an algorithm for generating robotic routes and movements.

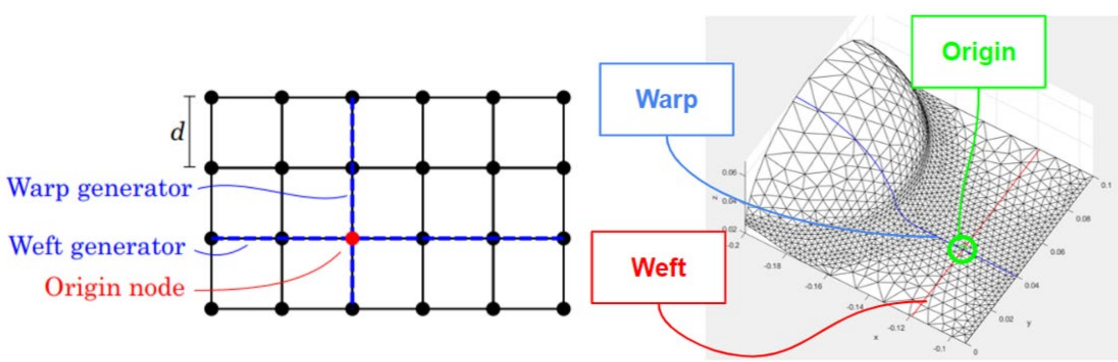


*Figure 2 - The fabric modeled as a grid of pin-joined cells. The origin node is chosen as starting point for weft and warp generation. On the right, an example of an origin node for a sub-surface from which the warp and weft lines start.*

The selection of the starting point is performed automatically by the algorithm but can of course also be done manually by the user. The previous division of the surface to be processed into sub-surfaces is used by the algorithm to place a starting point at the center of each mesh sub-surface, as the idea is to have a different simulation for each sub-surface of the mold surface and finally compare them.

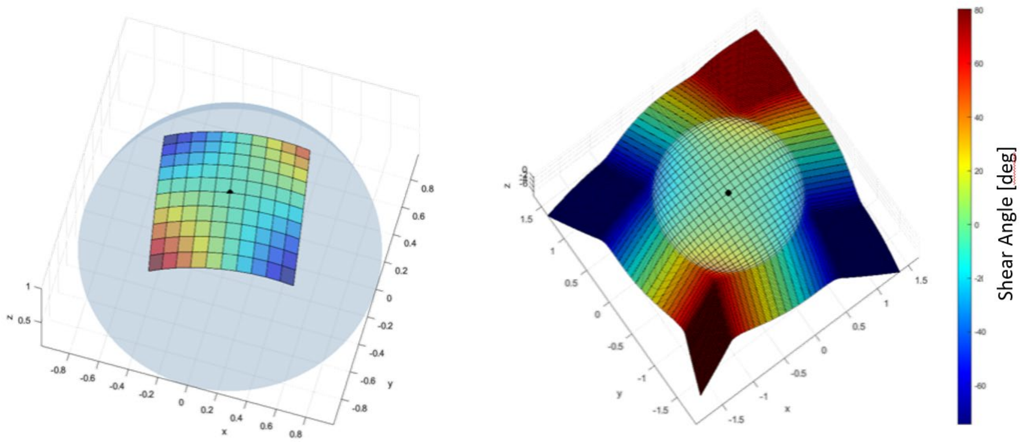


*Figure 3 - Examples of two grids placed on the same sphere. On the right side of the graphs there is a bar that indicates the size of the shear angle to which each grid cells are subjected. The Cartesian reference systems shown in the figure are related to the mold under consideration (to the sphere in this case). The two examples shown in the figure also differ in the orientation of the prepreg on the reference sphere: the image on the right shows an orientation of the fibers concordant with the axes of the X-Y plane (taken as a reference); in the image on the left, however, it can be seen that the fibers are not parallel to any of the axes.*

To simulate the behavior of the prepreg, a grid is created from a selected point, which will be considered as the starting point of grid creation. The edges of the grid cells represent fiber tows, and the grid nodes represent the cross-over points of the fibers (Fig. 2). Apart from the starting point, another crucial piece of information is the orientation of the prepreg fabric, indicating the warp and weft directions.

In the virtual environment, this involves generating two main curves from the starting point, which serves as one of the vertices of the first grid element and the origin of the grid. These curves depict the first two fiber filaments, representing the intersection of the warp and weft. Starting from the selected point, the triplet of verses matched to it consisting of the normal (N), tangent (T) and binormal (B) verses are considered. These reference unit vectors will be used for the identification of the main curves in the grid. Specifically, forming the principal curves will be the intersections with the discretized surface of the mold with the Normal plane and the Osculating plane. By default, the Osculating plane and the Normal plane are oriented parallel to the Cartesian planes ZX and ZY, respectively. This implies that a projection on the XY plane of the grid will see the fibers parallel to either the X axis or the Y axis. In the case of wanting to run a drafting simulation with a fiber orientation other than the default, the user can define an angle that will result in a rotation of the entire grid. The angle in question is then by default set equal to zero. In the case of a modification of this angle by the user, this value will represent the angle formed between the osculator plane and the ZX plane and the angle formed between the normal plane and the ZY plane: the angle is considered positive when the grid rotates clockwise around the Z axis.

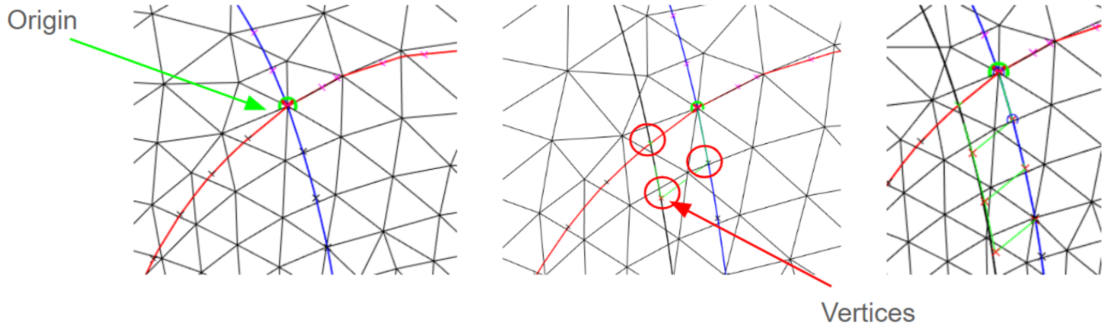


*Figure 4 - Stages of grid implementation: on the left, the origin node and main lines (blue and red), representing the warp and weft, are placed on the mesh; in the middle, the vertices of the first cell are identified according to the resolution chosen by the user; on the right, the generation of subsequent cells following one of the main lines, cells are created one at a time using the vertices of the previous cell as starting points.*

The creation of grid cells is an iterative process. The main curves divide the mold mesh into four sectors: the grid creation process creates the grid cells for each sector separately (the order in which the sectors are considered is not relevant). The first three nodes are identified on the main curves: the first is the origin point, the second and third are placed on the warp and weft curves respectively at a given distance. The user defines this distance, determining the size of the grid element: the distance chosen by the user is called "step" from now on. The accuracy of the simulation relies heavily on this variable: smaller grid elements result in a greater number of elements and more accurate results from the algorithm. However, it's essential to consider that a higher number of grid elements increases the computational load on the processor. Thus, finding the right trade-off between desired accuracy and computational load is a key consideration.
The fourth grid point is found by imposing two conditions: contact with the mold surface and maintaining the step distance between adjacent nodes (Fig. 4).

Because the user has set the step value, the sides of the grid cells are equal to each other: on a plane, the grid cells are always square. But on a non-planar surface, the cells deviate from the square shape: the further away from the starting point, the more the cells deform into rhombuses.

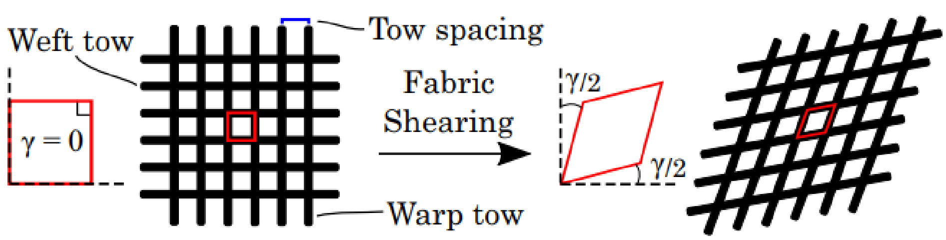


*Figure 5 - Shearing of woven fabric: the tows rotate at their cross-over points in the weave. The shear angle is denoted with γ.*

After the first cell is formed, the other cells are created following one of the two main curves. For the second cell, for example, the new starting point is the node of the previous cell placed on the main curve, the second one will be taken on the main curve one step away, the third node will be the fourth found vertex of the first cell, and the fourth and last vertex of the second cell will be found by imposing the same conditions as in the previous case: same distance from the adjacent nodes and contact with the mesh. The algorithm continues by forming one row of cells at a time starting with one of the main curvatures. The same procedure is repeated for the creation and positioning of all grid nodes until the entire surface of the given mold is covered.

The angle formed by the two sides of the cell represents the shear angle and, therefore, the deformation of the prepregs in that specific area during the layup.

The shear angles are then collected (Fig. 5). The algorithm is repeated by descending different points of the mold surface as grid origin and the cutting angles of the prepreg cells of each configuration are collected and then eventually compared. In the end, the point from which the resulting shear angles are smallest is chosen.

So far, the algorithm revealed the most suitable sub-surface for the beginning of the layup process for the specific selected surface. That is, the most suitable portion of the mold has been selected for the first contact between mold and prepreg and the first sub-surface to layup. Assuming that a mold of complex shape, consisting of multiple curvatures, is being considered, thus a mold consisting of multiple sub-surfaces, the need arises at this point to determine the best strategies for laying down the prepreg: it must be determined which portions of the mold surface should be laid down next. Essentially, the problem translates into the order of sub-surfaces affected by the robotic layup process.

Having determined the layup order, routes for the robotic layup can now be developed for the specific mold under consideration.  A sequence of paths is developed for each sub-surface. Taking as a reference the most significant edge of the sub-surface under consideration, a series of parallel paths are generated at a given spacing from each other: this spacing depends on the thickness of the roller with which the robot has been equipped.

**Results and discussion**

With the algorithm described above, a tool has been created for the automatic programming of the robotic layup for a generic complex-shaped mold. The user only needs to provide the discretized surface to the algorithm, and the program automatically works to provide the most suitable strategies for the surface to be processed. The implemented algorithm has been tested for different mold geometries. One of the main goals of this study is to be able to use the presented tool for robotic layup process with generic mold shapes: no matter how many different curvatures and sub-surfaces are present on the mold to be processed. For a better understanding of the results obtained, only two geometries have been shown as examples of the result provided by the implemented algorithm. Figure 6 shows the mentioned molds.

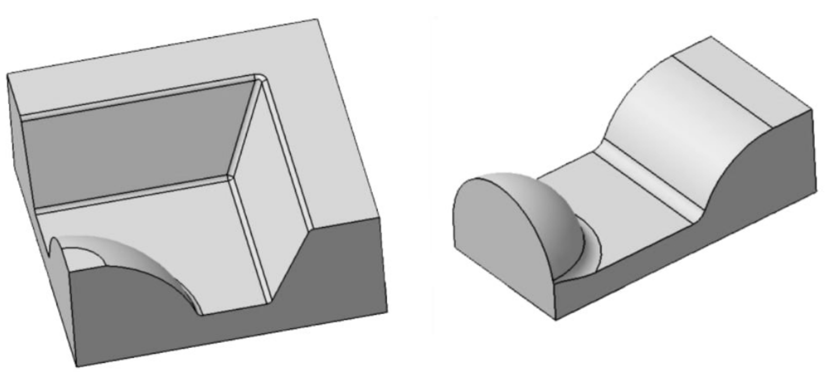

*Figure 6 - Two of the molds tested with the implemented algorithm taken as examples for the reported results.*

By detecting the curvatures present on the mold surface, the algorithm automatically divides the given surface into sub-surfaces: adjacent mesh elements having the same curvature are collected and grouped into sub-surfaces. In this way, the user can also choose to process the entire given surface or only a portion of it by selecting the desired subsurface to be processed: the user is prompted to click on the MATLAB graph of the surface by a message in the dialogue box and confirm the choice by pressing enter. Once the selection is made, the algorithm generates a new discretized surface composed of only the user's selection (Fig. 7), and the algorithm proceeds as described above.

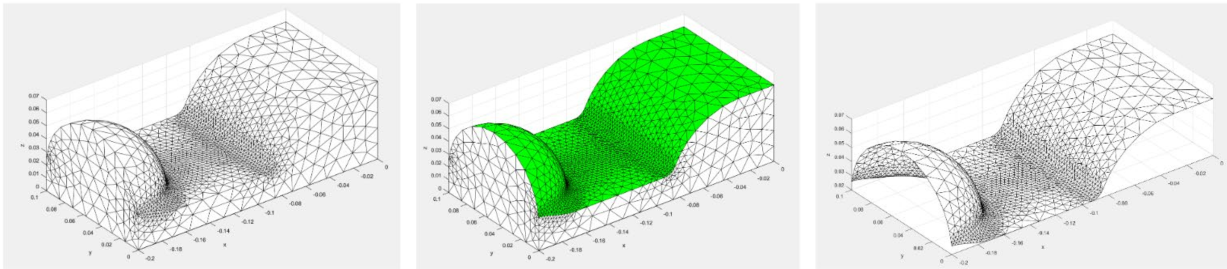

*Figure 7 - Sub-surface selection process: on the left, the mesh of the entire mold; the user is asked to click on the mesh areas of the mold surface to be processed during the layup process, and the selected sub-surfaces are highlighted in green (center); on the right, a new mesh is created consisting of only the selected parts of the surface.*

The selection allows reducing the number of elements to be processed during the flow of the algorithm: thus, the load for the CPU processor will be reduced proportionally.

Subsequently, the algorithm goes on to identify the sequences of the selected sub-surfaces. Each selected subsurface is associated with an origin point, and an iteration is performed for each of these origins. The origin establishes a specific scenario that the prepreg will find during layup. This means that as many sub-surfaces are selected, as many scenarios will be present.

For each origin point, the draping model is run, which will provide an array in which the shear angles of the grid elements are collected for that specific configuration. Then an average shear angle is associated with each subsurface. The average shear angle represents the average deformation that the prepreg will undergo during the layup process in that specific configuration, i.e., starting the layup from the sub-surface associated with the origin point under consideration.

This means that the lower the average value of the shear angle, the less defects will be encountered during the layup process, consequently leading to a better quality of the component produced both from the point of view of the uniformity of the surface realized, which will be closer to the processed mold, and consequently also from the point of view of aesthetics, and the point of view of mechanical characteristics.

This part of the code is executed for each subsurface and the average shear angles are compared: the configuration that shows the lowest average shear angle will be chosen as the best part of the mold surface to start the layup.

Then, this information will be collected for the second phase of the code, in which the second-best subsurface to be covered is identified. The loop continues until all the sub-surfaces are processed and the sequence of sub-surfaces is finally identified.

In the Fig. 8, the result of each iteration of the loop is shown for two different molds taken as examples: the sub-surface to be processed is shown in yellow; the surface identified as the best sub-surface to be chosen in that specific iteration is identified in green.

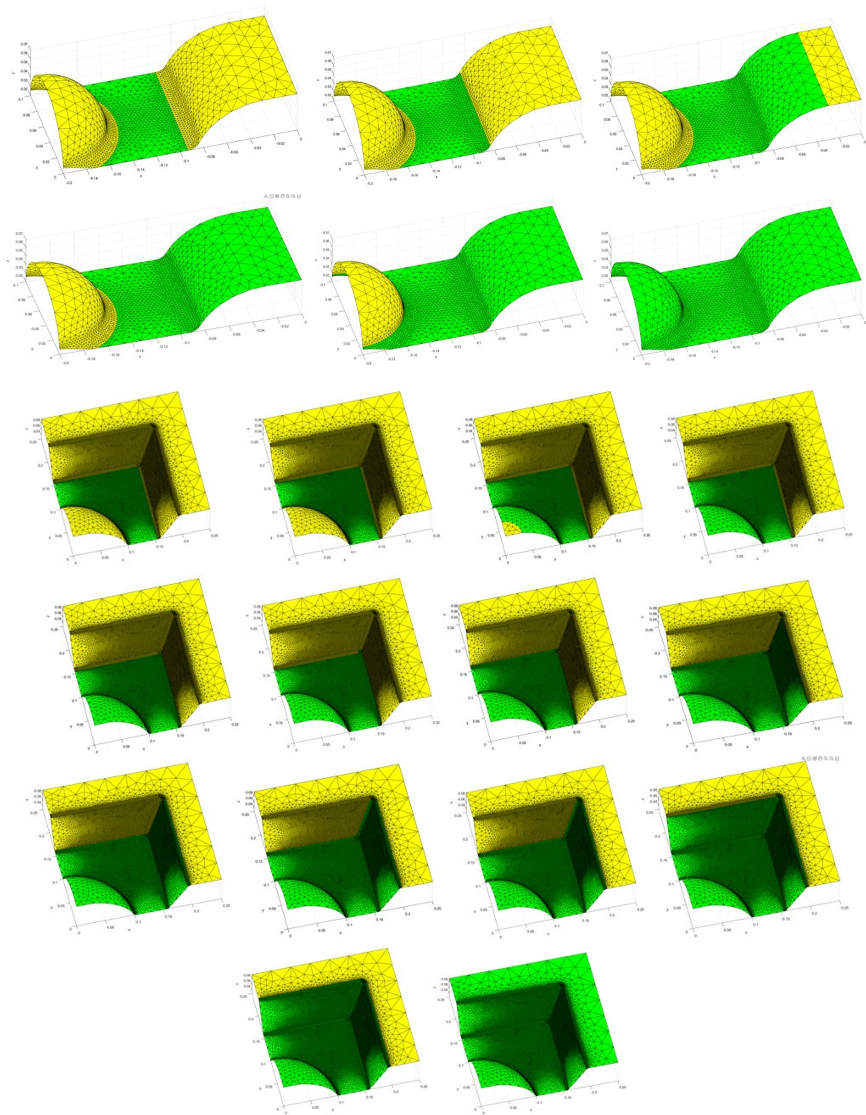

*Figure 8 - Examples of determining the order of sub-surfaces to be processed during the robotic layup process. Sub-surfaces not yet chosen are colored yellow; chosen sub-surfaces are colored green as they are identified as the most suitable surface in that particular iteration. Above is an example of a mold in which six sub-surfaces were chosen; below is a more complex mold in which fourteen sub-surfaces were chosen.*

Once the order of the sub-surfaces has been identified for the layup process, the paths for the robotic arm are implemented. For each sub-surface, a sequence of paths is generated that are all parallel to a border of the sub-surface under consideration that is considered most significant due to its extension. These paths are spaced by a distance that corresponds to the thickness of the roller chosen to lay that specific part of the surface. The selection of the roller is done automatically by the algorithm by comparing the radius of curvature of the sub-surface under examination with that of the available rollers: if the curvature under examination is very small compared to the rollers with which the robotic arm has been equipped, that surface is considered as a fitting and is treated with a narrower punch and a roller with a fitted edge that can better process that area. Again, for the same sub-surface, the next sequence of paths is generated following a direction perpendicular to the previous one in order to consolidate the area of surface that has just been laid (Fig. 9).

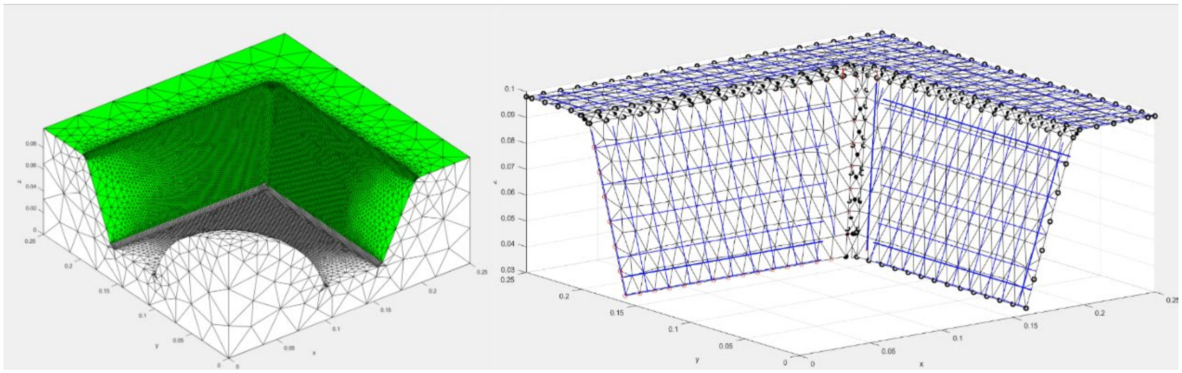

*Figure 9 - On the left are the selected sub-surfaces colored green; on the right are the paths generated for the specific selection.*

In order to correctly interpret the proposed work, it should be kept in mind that the algorithm implemented during the present study is intended to program robotic movements during the robotic layup process. For the effective application of the programmed movements, there is a need for careful set-up of the equipment and the mold. Not least is the correct positioning of the prepreg sheet in accordance with the drafting schedule calculated by the algorithm. If, for example, the algorithm has estimated that the best starting point of the layup is a concave area of the mold, proper pre-positioning of the prepreg in that area will promote the proper execution of the layup, avoiding unwanted adhesions of the end-effector with parts of the prepreg that are not intended to be processed at that particular point in the process. At the beginning of the implemented code, the dimensions of the rollers used (in terms of thickness and diameter) as well as the configuration of the end-effector are set to take into account the overall dimensions. The correct choice of rollers for the particular mold to be processed is an important aspect to consider. If the mold to be covered is small or has very tight radii of curvature, it is important to properly equip the robotic arm with appropriately sized rollers.

## Summary

The work presented in this paper provides an algorithm for automated programming of the lay-up of prepreg sheets on molds of complex geometry. This tool not only automatically implements the robotic lay-up movements and provides a simulation of them, but also automatically identifies the lay-up strategy that best fits the mold specified by the user. Clearly, the end user always has the possibility of modifying the decisions made automatically by the software. But what has been implemented during this work also allows the robotic layup process to be faster in the design phase of the layup strategy, as well as in the practical phase performed by a robotic arm and no longer manually by a laminator. This also entails a reduction of human intervention in decision-making and planning processes, which could be reduced to a simple supervision of the results produced by the computer at the end of the implemented code. In addition to this aspect, the following benefits were also achieved:

- the most suitable layup strategies can be chosen for a specific mold;
- the presence of defects could be reduced;
- coding and testing time can be optimized, and the process can become faster.

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