Automated programming for the robotic layup process

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Keywords: Robotic Layup, Automated Layup, Prepreg, Fiber Placement, Industrial Robot

Abstract. Hand layup is still appreciated in modern industry for processing composite materials. Since is a manual process, reaching a standardization is impossible and this limits the applicability of this process. AFP and ATP offer a good level of automation and standardization, but both these processes are effective on simple-shaped surfaces. The conventional manufacturing processes have been increasing their level in automation thanks to the implementation of tooling machines and software that are able to automatically generate routes and tasks for manufacturing of a desired component. The goal of this research project is to take a step forward in the evolution of CAE software for tasks and routes management of the robotic layup process. In this paper a script implemented with MATLAB is described. The implemented script can automatically generate movements for robotic layup given a desired mold: starting from a user-given surface, the surface can be divided into sub-surfaces, and the software can automatically generate paths for each part of the surface according to the manual techniques studied by professional laminators.

Introduction

Advantages properties of fiber reinforced polymers (FRPs) have promoted their wide usage in several applicative sectors, ranging from aerospace, automotive, through to naval and construction industries [1] to improve the performance and reduce the weight of their components [1–14]. Advanced FRPs are multi-phase materials made of continuous reinforcing fibers, oriented in one or more specific direction, embedded within a polymeric matrix.

Nevertheless, despite of high specific strength and stiffness, corrosion resistance, and design flexibility, FRPs are affected by some drawbacks limiting their further application. As a multi-phase material, FRPs have an anisotropic behavior dependent on reinforcements' orientation [6]. This leads to excellent performance under longitudinal loading, but scarce (matrix dependent) behavior in case of transverse loading. In most lightweight composites, matrix is constituted by polymeric materials, both thermosetting or thermoplastic resins, whose main roles are to keep together the fibers, transfer and distribute loads, and protect them from the atmospheric agents. To improve the material properties and reduce anisotropic behavior, the most used strategy is to lay the fibers plies in different directions [15].

Hand layup has been the earliest manufacturing technique used for shaping composite products [16]. Also classified as a no-industrial process, this technique offers the advantage of low-cost suitability for the production of small batches. But as a manual process, the hand layup carries all the problems lead by the operator actions. From a quality point of view, this means that it is impossible to reach a standardization of all the pieces produced [4]. To improve the repeatability and reduce the human intervention, other manufacturing processes have been developed such as, among others, liquid composite molding, pultrusion, filament winding. Through the years, most of the manufacturing processes to fabricate fiber-reinforced composite products are based on conventional techniques such as the autoclave. But the demand for automation is rapidly increasing in the industry in order to achieve lower costs, repeatability, and reduction in material scraps [5].

Materials Research Proceedings 28 (2023) 367-374 https://doi.org/10.21741/9781644902479-40

Recently, the application of automated manufacturing to composite layup led to the development of an innovative process, namely robotic composite layup [5], based on the replacement of human operations by one or more opportunely programmed and eventually collaborative robots [17].

During past few decades, advancements in automated composites manufacturing processes such as, automated fiber placement (AFP) and automated tape placement (ATP) (or other commonly known name of automated tape layup, ATL) technologies have revolutionized the fabrication of aerospace components. Major aircraft manufacturers have been utilizing automated techniques for many years now in their production lines to rapidly manufacture their flagship aircrafts such as Boeing 787 and Airbus A350 XBW, containing more than 50% composite parts by weight [7], [8]. Compared to other aerospace manufacturing techniques e.g., resin transfer molding (RTM), AFP and ATP systems are the most advanced and commercially used automated machines for large-scale aerostructures manufacturing. In terms of functionality, both AFP and ATP systems are very similar even though both methods use different approaches to fabricate specific components using resin pre-impregnated fabrics (commonly known as prepregs) [9]. One of the major differences between the two processes is that the AFP machine places multiple narrow pre-impregnated fiber tows whereas the ATP machine lays up larger and wider unidirectional tapes [9], [10]. Instead of conventional robots, both AFP and ATP use machine tool-based processes that can significantly reduce the cost of composite parts, especially large components, main wing structure, ribs, fixed trailing edge, nacelle structure, spoilers, flaps, ailerons, and tail cones [5]. Despite the benefits in terms of automation and reduced human involvement, these two processes are expensive: they are effective only for large parts with low to medium geometric complexity and have been implemented in those industrial fields capable of justifying high capital and operating costs. AFP/ATL are therefore technically and economically incompatible with the production of small to medium-sized components or complex-shaped parts, or with production volumes that cannot justify the usage of such expensive systems. In such situations, manual processes are needed leading to variability in part quality depending on the experience of each operator [18]. In this context, the robotic layup process has been developed to offer a high level of automation and standardization, reducing human involvement while at the same time offering the ability to process even complex shapes. Many efforts have been made in recent years to improve robotic processes and make them free from the actions of operators. Most of the knowledge about prepreg layup has been developed from the personal experience of professional laminators, who have implemented and collected strategies and techniques over the years to improve the layup process and reduce time and defects. Transferring this knowledge to a robotic process requires the constant attention of a professional laminator when coding robotic movements. The goal of this research project has been to implement a code capable of automatically handling the laying of a complex shaped surface. Another constraint that was considered during this study is to plan the entire layup of the mold surface using only one properly equipped robotic arm and clamp system. As demonstrated in previous work, processing the layup with two or three collaborative robots can certainly provide more accurate robotic handling as well as can promote the success of the process, but all this make the process complex and economically disadvantageous.

The implemented algorithm is able to handle a set of strategies and techniques on different mold geometries. The experience of professional laminators was translated to be used with a robotic arm equipped with a specific end-effector.

Materials and methods

In order to collect and organize the techniques implemented by professional laminators, CAE software has been used to implement an algorithm to manage the surfaces of each mold analyzed and manage layup strategies. The software used has been MATLAB. "Gmsh," an open-source CAE software widely used for FEM analysis, has been used for mesh generation.

Complex-shaped molds have been used during testing to make the experimental campaign as generalizable as possible. The three molds used for the test campaign have been designed to be a workbench for the implemented algorithm. They have different shapes and require different layering strategies. They include planes with different inclinations, curved parts, fillets, and spherical parts. Moreover, they also include concave and convex parts that require specific steps to be processed.

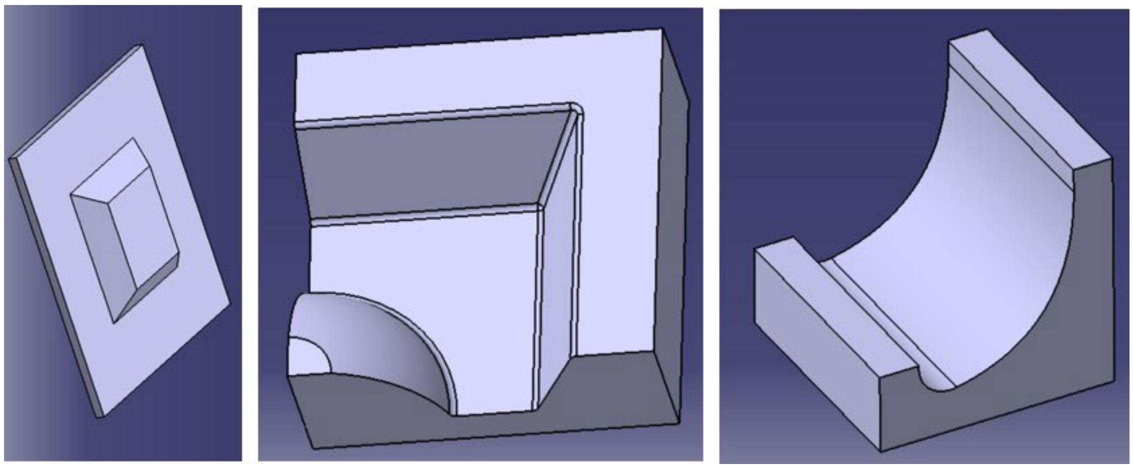

Fig. 1. The molds used as workbench

As a collaborative robotic, a Comau Smart SiX 6 has been used, which is a robotic arm with 6 degrees of freedom (DOF). All the simulations are performed in MATLAB environment and the robotic process is simulated thank to Robotics System Toolbox add-on. The information regards the robot is included in the URDF model which uses the XML standard to describe a robot which includes kinematic and dynamic behavior, visual representation, and collision model.

For this test, the end-effector used is composed of three terminals: cylindrical roller for flat surfaces, a profiled roller for fittings and small radius curvatures, and a punch for consolidating prepreg in corners and tight parts. The cad models of the end-effector and the mold have been made with CATIA V5 CAD software, loaded into MATLAB environment, and then the end-effector linked to the robotic arm model and mold placed in desired position inside the virtual working area of the robot.

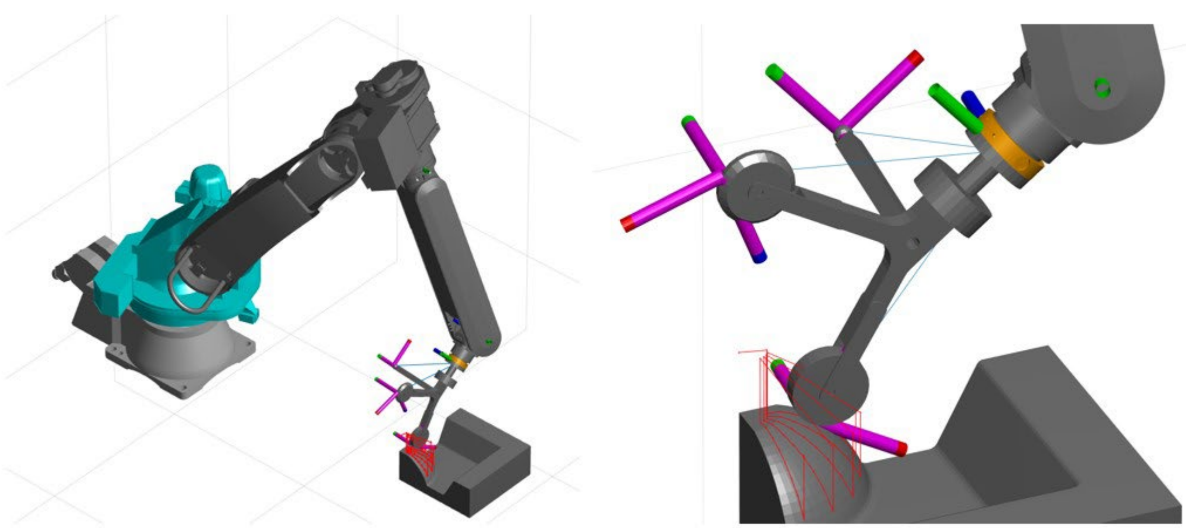

Fig. 2.The robot, the end effector, and a mold imported in MATLAB environment

The implemented algorithm is able to recognize the different parts of the surfaces of a mold and apply the correct strategies for the layup phase.

The process begins with loading the mesh of the mold surface. Triangles have been chosen for the elementary entities of the mesh. The mesh includes information about the coordinates of the points and how they are connected together to form the triangles. Cleaning the surface from unnecessary points is the first step: the mold mesh also includes sides that are not required for layup. The sides of triangles were used to identify the normal vector of each elementary surface: the vector product of two sides gives a vector directed to the normal of the plane identified by the triangle. By placing this vector in the center of the triangle and considering only its modulus, the normal vector of the triangle has been obtained. The normal vectors are then used to identify the sub-surfaces that compose the mold surface. An algorithm has been implemented that can analyze the orientation of the normals and group triangles with the same orientation in space and collect them into an array. At this point, the mesh, mesh nodes, and triangles are ready to be used in the next step, where paths are defined according to the strategies of experienced laminators.

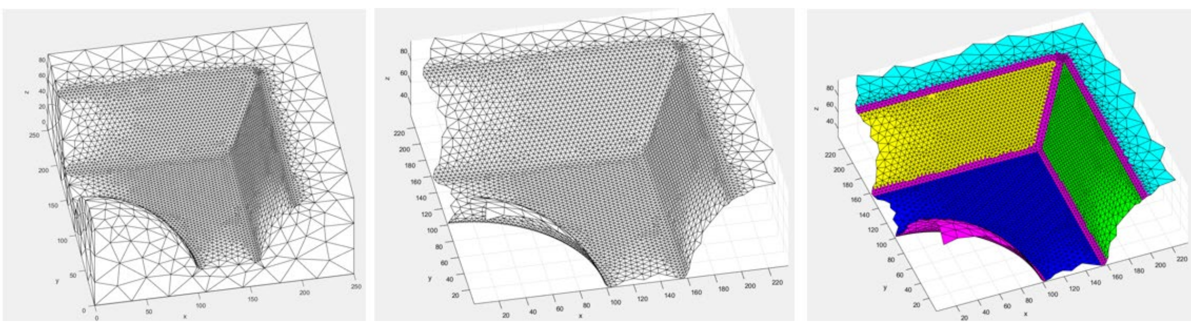

Fig. 3. The mesh of a used mold (left); the same mesh cleared of elements not to be processed (center); the mesh divided into sub-surfaces (right)

The strategies have been translated into routes and tasks to be performed in a specific situation. Starting from a literature review, the approaches used during the experimental trials have been collected. Following the most common scenarios are listed with the approaches used in previous works.

The main human techniques have been listed in the work of M. Elkington et al. “Hand layup: understanding the manual process” [19]. Eight different techniques used in different scenarios are described in this paper: one handed guiding; two handed guiding; manual folding; hoop shearing; double-tension shearing; tension-secured shearing; tension and sticking; mold interaction shearing. Some of these techniques involve both of the operator's hands. But in most cases, careful selection of a prepreg clamp system or choice of starting point can enable the robot to replicate the same pressure applied by the operator.

An important aspect is the definition of the boundaries of each sub-surface. These boundaries are defined by the user with a manual selection of points. In this way, it is possible to define how the parts of the surface are connected to each other and their relative inclination.

Another challenge is the choosing the areas of the sub-surfaces to process first. The friction between mold and prepreg is very high (and even higher between two consecutive layers). For this reason, starting layup from the correct part of the surface is crucial to the good result of the process. For example, if the surface to be treated has a concave shape, starting with the upper parts of the mold with the idea of then moving to the lower areas may lead to insufficient prepreg to cover the lower part, resulting in bridging defects (Fig. 4A).

The same could happen with an edge that joins two or three sub-surfaces with different inclinations. In these areas, depending on the order of the processed surfaces, two different scenarios could occur: an excess of material, which could lead to wrinkling; or a deficiency of material, which could lead to bridging [20].

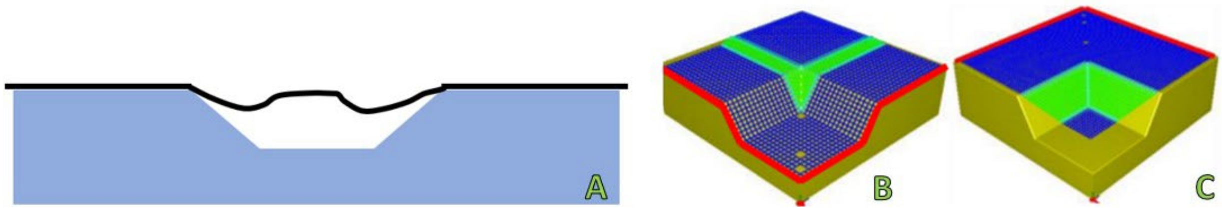

Fig. 4. On the left (A), an incorrect choice of starting point that led to the bridging defect; on the right, a mold processed in two ways: in the first (B), the process began by consolidating the lower part (red lines); the second (C) began by consolidating the upper part. The green areas represent the portions of prepreg where the defect occurs.

The Fig. 4B and Fig. 4C show that different starting positions lead to the two situations mentioned. In case shown in Fig. 4B, the layup has started consolidating the lower part and then moving to the upper part: the green part represents the area where there is excess material, which led to wrinkles. In case shown in Fig. 4C, the layup has started from the upper part: the green part is not enough to cover the remaining area, which led to a bridging defect.
To avoid the problems mentioned above, the algorithm is able to study the shape of the surfaces and whether there are any concave or convex parts. If so, the software implements routes starting from the bottom of the concavity or the top of the convexity: the layup will then begin by laying the material starting from the proper sub-surface. In this way, the amount of prepreg will be sufficient to cover that part of the surface avoiding defects such as bridging.

Several cases are included in the algorithm that are based on the experience gained during previous work and the experience of professional laminators. The algorithm is able to understand the inclination or curvature of sub-surfaces. For each subsurface, the shape of the surrounding parts is detected. Through the analysis of the normal vectors of the triangles and the coordinates of their centers and nodes, it is possible to understand whether a subsurface is located, for example, at the bottom of a concave mold. In this way, it is possible to determine the most appropriate sub-surface to start layup.

After sticking the first subsurface, the algorithm is programmed to start consolidating the nearest fittings, and routes are designed starting from these edges. Moreover, processing a subsurface requires gradual movement. For this reason, each part of the surface is processed in steps: movement along the entire length of the subsurface is avoided and steps are chosen according to the extension of the surface and the size of the tool used.

Results and discussion

The implemented algorithm can process the given mesh elements and generate specific routes based on the experience of professional laminators. From the experiences gained in the works mentioned, starting on the proper side of the mold surface is critical to achieving a good layup. For the given molds, the algorithm proposed the following sub-surface sequence (Fig. 5).

In mold "a," the algorithm chose to start from the top and then move down toward the base of the mold. The reason for this choice is that the elements of the other sub-surfaces gradually go down without a subsequent ascent. In mold "b," which is probably the most complex, the algorithm chose to start at the bottom of the mold, then consolidate the neighboring fillets, and then work its way up. In this case, the chosen part represents the bottom of a cavity. Therefore, in order to have enough material to cover the other parts, the streaking action of the end effector on the prepreg must start from that surface. In the "c" mold, on the other hand, there are two planes at different heights joined by a concave surface. In this case, the best solution would be to start from one of the two planes by gradually moving upward. The algorithm chose to start from the higher plane because this choice is shared with other cases contained within it. In all these cases, pre-shearing prepregs can reduce the occurrence of defects. After consolidating each subsurface, the algorithm generates instructions to consolidate neighboring fittings before moving further. The solutions shown are just a proposal derived from a series of cases included in the implemented algorithm. Of course, the end user can control these sequences by clicking on the mesh elements: after rejecting the proposed solution, the software asks the user to select the sub-surface where they want the layup to begin.

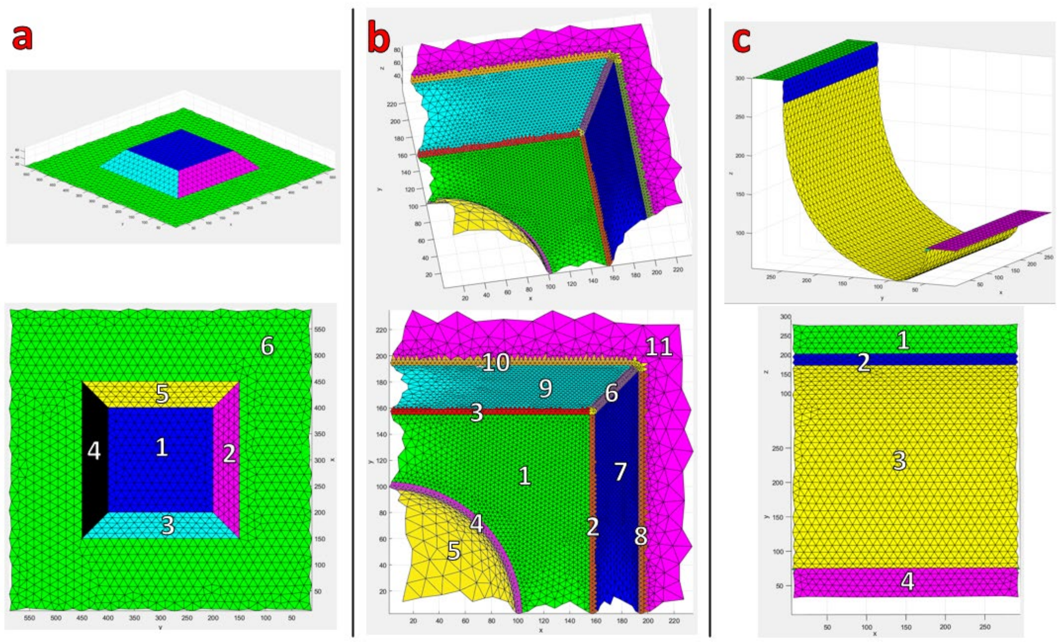

Fig. 5.The meshes of the molds in which the order of layups for each mold is indicated.

It is also possible to introduce new cases to increase the range of different recognized scenarios.

Summary

The implemented algorithm makes possible the automatic handling of mold meshes in order to design their layup. Since automatic actions have been implemented, the design time for an assigned mold to be processed is reduced: trajectory calculations are automatically performed by the software, which also generates the correct positioning of tangent, normal, and binormal vectors. The proper management of these angles prevents the occurrence of unwanted collisions during layup. The operator who now sees a routing solution offered for the end effector is still required to perform a check, thus a simulation of the process. But the time to calculate the positions of the mentioned vectors has still been reduced.

This results in faster reconfiguration and adaptability of the used resources, i.e., the robotic cell, and also reduces its actual utilization time.

Clearly, the end user is free to reprogram the layup to his liking.

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