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Defects Reduction in the Robotic Layup Process

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Abstract. Robotic layup is a novel process developed to face the increasing demand for automation, flexibility, repeatability, and achieving high-quality composite materials in relevant industry fields, such as aerospace and automotive. This process is based on laying prepreg tissues on a mold using the action of a robotic arm equipped with a specific end-effector, which is usually composed of rollers and punches. The main drawback of the robotic layup is the occurrence of wrinkles and defects while moving, placing, and processing the pre-impregnated tissues. This issue is particularly evident in the processing of complex-shaped surfaces. The robotic arm cannot replicate exactly the movement of a human operator, following the geometry of the surfaces with a proper angulation like a human wrist. Moreover, operator hands can be set in a different shape just changing the configuration of the fingers, adapting themself in different curvatures. The demand of the industry to improve automation requires that the robotic manufacturing systems replicate as much as possible the gesture of the operator. Following these requirements, this study has focused on the recognition and discretization of the surfaces to be processed, in order to allow a robotic arm to better reproduce the movements of the laminators thanks to a better management of the end-effector. Moreover, an end-effector capable of replicating one of the techniques most commonly used by professional laminators on molds with complex geometries has been designed.

Introduction

The industry is constantly seeking out advanced materials and manufacturing techniques to improve the performance and reduce the weight of their components [1]-[16]. Advanced composite materials can offer several advantages, making them appealing for many important industrial fields looking for high-performance components and goods. The increasing request from the industry of lightweight multi-materials components pushed the scientific community to devote remarkable efforts towards the manufacturing, modeling, and processing of high-quality fiber-reinforced composite [1]. Advantageous properties of fiber-reinforced polymers (FRPs) have promoted their wide usage in several applicative sectors, ranging from aerospace, automotive, to naval and construction industries [2]. Advanced FRPs are multi-phase materials made of continuous reinforcing fibers, oriented in one or more specific directions, embedded within a polymeric matrix.

One of the main drawbacks in FRPs is related to the poor surface properties. Nevertheless, recently, the development of manufacturing techniques to metalize FRPs is providing them with interesting surface properties [3]. Despite 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. This leads to excellent performance under loadings along the fiber's direction, but scarce behavior in the case of transverse loading. In most lightweight composites, the matrix is constituted by polymeric materials, thermosetting or thermoplastic resins, whose main roles are to keep together the fibers, transfer and distribute loads, and protect them from the atmospheric agents. Thanks to their properties, the industry's interest is growing, prompting research to address the constructional difficulties of these materials.

Hand layup has been the earliest manufacturing technique used for shaping composite products, also classified as a non-industrial process. This process involves manually laying down individual layers or plies of resin pre-impregnated fabrics, commonly known as prepregs. This consists of fibers, which are pre-impregnated and joined with resin and arranged in unidirectional towns. The layup process is based on manipulating each ply into a mold shape by hand and then firmly stuck to the previous layer or mold surface leaving no air pocket between plies. 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's 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 manufacturing industry of composites in relevant and import key fields, such as aerospace, aeronautic or automotive, in order to achieve lower costs, repeatability, in-process inspection, and reduction in material scraps [5].

During the past few decades, advancements in automated composites manufacturing processes such as, automated fiber placement (AFP) and automated tape placement (ATP), which are also commonly known as automated tape layup (ATL), technologies have revolutionized the fabrication of aerospace components (figure 1) [6].

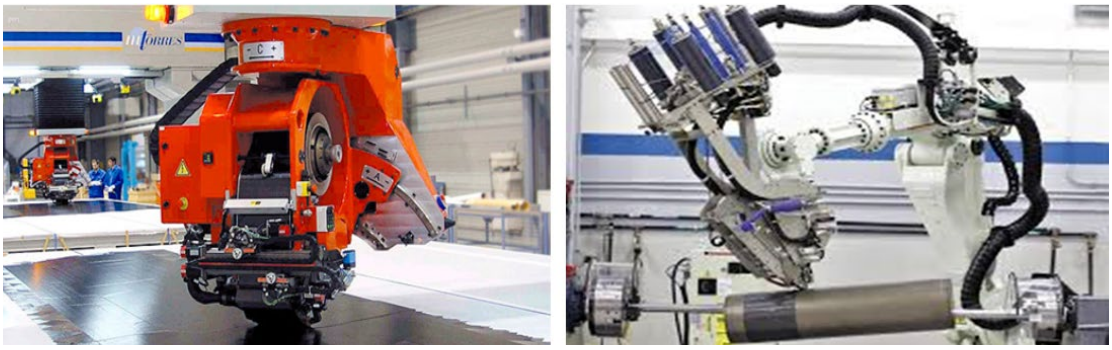

Figure 1- On the left, an ATP machine; on the right AFP machine [5].

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 APF machine places multiple narrow pre-impregnated fiber tows whereas the ATP machine lays up larger and wider unidirectional tapes [10].

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.

By addressing these issues, the robotic layup has been born: technological development has allowed the robotic arms to replicate the gesture and techniques performed by the operator, making the robot usage the most suitable to replace the human movements during the hand layup process.

This process has proved to be effective in a wide range of applications and mold geometries and can be performed from a multiple-robot cell to just a single robotic arm. In any case, the robot is equipped with a specific end-effector mostly composed of rollers and punches.

As in manual processes, also during the robotic layup, some defects occur mostly related to whether the prepregs cannot perfectly follow the shape of the surface mold during the laying phase. Moreover, in robotic processes, there is not the same adaptability of the human hands to grasp and lay prepregs: laminators can adjust their hands to follow the geometry of the mold surface by adjusting the position and angle of their wrist and fingers. With a robotic arm, the adaptability is expressed by the end-effector used, as well as good planning of the paths and movements. The end-effector consists of a static part of the robot, which once designed and built, cannot evolve to deal with geometries and contexts too different from those for which it was made.

Thus, in order to improve and generalize its use, there are two main ways to proceed. The first one consists in enriching the end-effector with more tools, for instance, by implementing more rollers and punches on the same end-effector. The second way is to make the structure of the end-effector dynamically reconfigurable, giving it the possibility to change its shape during the laying phase, changing consequently the action applied on the surface to be processed. Both solutions bring their flaws. Implementing multiple tools on a single terminal increases its size, and consequently, decreases its manageability and use in tight spaces. Making the terminal reconfigurable, on the other hand, increases its degrees of freedom, causing greater complexity in end-effector management.

In this study, a hybrid solution between the two possible alternatives has been conceptualized.

The investigation has led to the realization of an end-effector capable of replicating the action exerted by the hands of professional laminators during manual lay-up.

Materials and Methods

The robotic layup has been developed to replace, or at least replicate, the human gestures performed by the professional laminators during a hand layup process. Indeed, the whole process has started from a careful analysis of the laminator's techniques. Experience has carried out the laminators to develop some gestures which lead to a reduction of defects and working time of the laying phase [11]. Studying the manual gestures has led to a better understanding of the process and this has allowed to design a specific end-effector and also to set the base for initializing the coding phase of the robotic arm.

In order to make the research results as general as possible, a mold with a complex geometry has been used. The end-effector has been designed including two rollers and a little punch for angles and vertexes (Figure 2).

Figure 2 - The end-effector and mold used.

As a collaborative robotic, during this research study, a robotic arm has been used: Comau Smart SiX 6 1.4 with 6 degrees of freedom (DOF).

Mold mesh discretization. The instructions taken by the robot are points coordinates and equations of motion that the tool has to follow. For the identification of the points, it is possible to proceed either through the use of photogrammetric methods or by importing the CAD model of the mold. Even though the second method is not accurate as of the first, because it's referring to a perfect geometry given by the software CAD model and not affected by manufacturing defects, it has been here adopted due to the simplification in the surface elaboration and discretization. Subsequently, the CAD file has been exported in Standard Triangulation Language format (usually known as STL format), and starting from it, the coordinate matrix of the mesh nodes has been generated. The tool chosen for the grid points generation was "Gmsh", an open-source software CAE widely used for FEM analysis.

Mold mesh management and processing. The software chosen to manage and process the cloud points, and also to write the scripts of the code to control the robotic arm, has been MATLAB, a CAE software provided by MathWorks.

Robots need specific instructions which are mainly divided into two parts. The former regarding the tool paths generation in geometric terms: the system receives information about the mold shape, the tool, the sequences, and the strategies to apply, and it processes them providing an ordered set of cartesian coordinates with their orientations, which the tool must follow as output. The latter, concerning the generation of the trajectory from the kinematic-dynamic point of view, where the system works on the outputs of the first step, associates them an equation of motion and any boundary conditions about the specific position, orientation, speed, and acceleration of the various axes of the robot [12]. In this part, movements calculation takes place in terms of angle value for each joint of the used robot. All these movements are subsequently translated in a programming language able to be understood by the control unit of the robot.

The first part starts loading the acquired mold mesh in the MATLAB environment. For each elementary entity in the mesh, its orientation in space is calculated. This value is used to identify the different curvatures of the mold surface. By using a graphical interface, the user can insert the desired strategy in terms of the selection of surface portions to be machined and the type of movement to be implemented. Then, the coordinates' identification of the ideal points belonging to the trajectory has been performed. These points have been subsequently compared with the real points presented on the mesh given by the discretization surface to identify the real waypoints. In order to identify the closest real point on the mold mesh, a tolerance range has been set by the user: smaller is this value, higher will be the density of the points and higher will be the elaboration time by the processor. In case there is no point inside this range, the distance will be increased of a small delta set in the algorithm by the user until a point will enter in the range. The coordinates have been collected and the Frenet-Serret triad, also known as TNB (Tangent, Normal, and Binormal), has been defined for each point of the path.

Implementation of robotic arm movements. In addition to the information regarding the trajectory points, it is required also the configuration of the robotic arm and its end-effector.

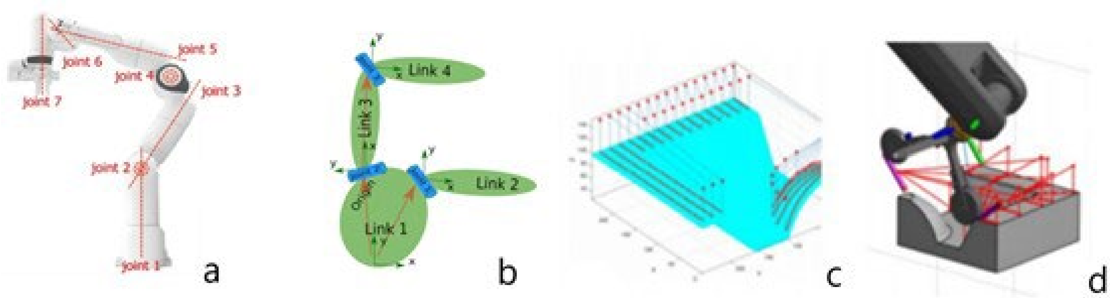

Figure 3 - a) schematic representation of a robotic arm with highlighted joints; b) general URDF model of a robot; c) passive and active movements; d) process simulation.

This information 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. Then, the movements of the robotic arm are calculated, also reproducing a simulation of the laying process (figure 3). Subsequently, the positions of the joints are translated into the PDL2 language, which can be understood by the manipulator control unit.

Results and Discussion

Regarding the code part that manages the surface geometry and generates routes and tasks, an outcome achieved during this study is the identification and processing of the mesh. The implemented algorithm proved to be effective in recognizing and processing the geometry which defines the mold surface. This capability is essential for all the further processes design and their industrial applications since it allows users to process different and complex shapes.

The points cloud coordinates of the mesh are integrated with information about how the different points are connected to form the elementary triangles that define the discretized surface of the mold. Using these connections, it has been possible to implement an algorithm that is able to estimate the orientation of each triangle by calculating its normal vector (Figure 4).

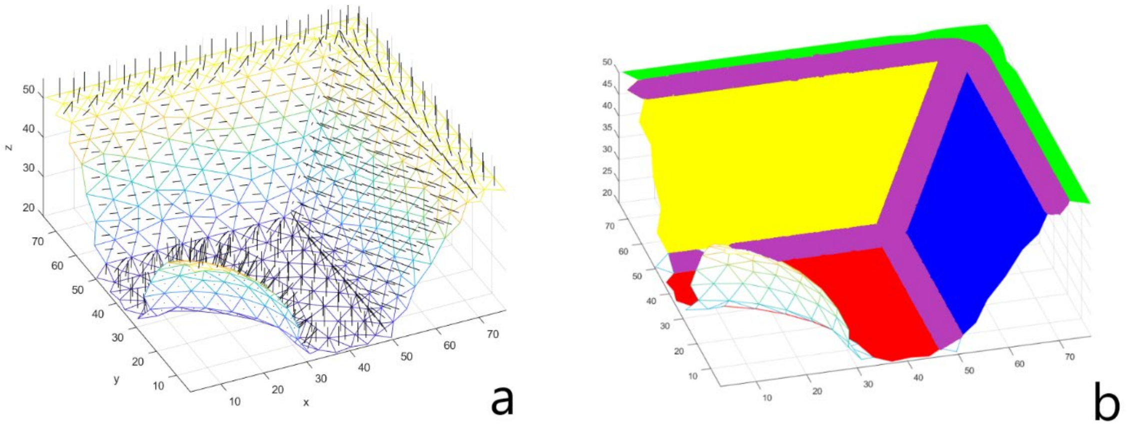

Figure 4 - Meshes of the mold surface: a) in black are highlighted the normal vectors referring to each elementary entity of the mesh; b) each recognized part of the surface has been indicated with a different color.

Using these values, it has been also possible to divide the surface into different entities, which are composed of points that had a common angle (for example, a horizontal plane or an oblique plane).

Moreover, by comparing the angle of every single waypoint with the closest ones, it has been possible to automatically recognize the trend of the specific trajectory on which the analyzed waypoint is positioned. In this way, each trajectory has been actually subdivided into many sub-trajectories, each of which identifies a different curvature. In particular, it is possible to automatically evaluate if a certain trajectory is formed by flat parts, identifying moreover its angle, or by curved parts identifying the radius of curvature.

Therefore, these values are also important for the management of the end-effector angle. Reading the angle of the specific part of trajectory to be covered, it has been possible to modify the angle of the end-effector properly from time to time: the angle is managed by a variable parameter, which can dynamically assume different values on every single waypoint of every single trajectory.

Another relevant outcome has been the design of an improved end-effector. The expert laminators increasingly make use of the technique known as "Tension-secured shearing" as the complexity of the mold geometry increases (figure 5).

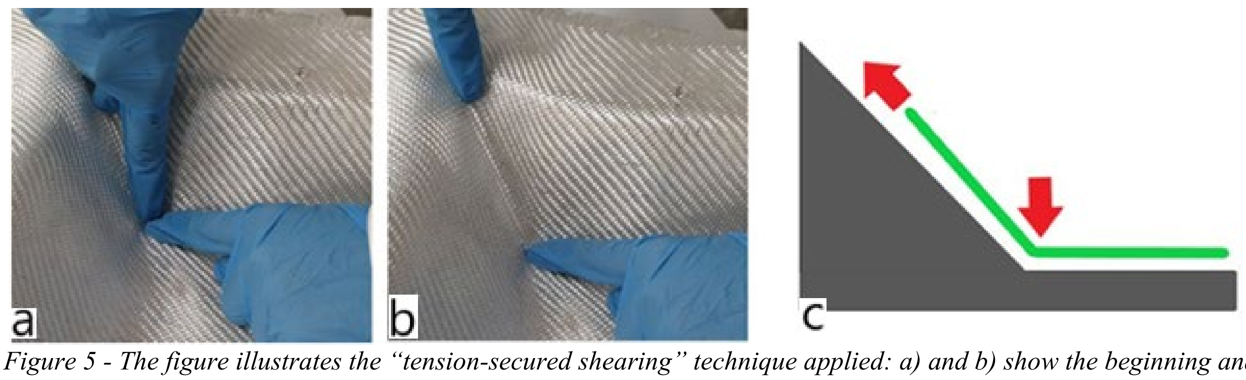

Figure 5 - The figure illustrates the "tension-secured shearing" technique applied: a) and b) show the beginning and the end of the movements performed by a laminator; c) shows a schematic representation of the forces applied and their directions.

This technique involves the laminator securing the prepreg to a mold vertex by applying pressure, then proceeds to tension the following part of the prepreg (figure 5.c), preventing it from immediately adhering to the incident surface. Afterward, the laminator inclines the fabric more, making it adhere to the surface. This technique avoids the formation of defects, such as bridging (non-adhesion of the sheet at the edges), thanks to the persistent pressure applied until complete adhesion to the adjacent surface.

In order to replicate this technique as much as possible, a new end-effector has been designed that can simulate the operation described above. It is composed of three tools: two rollers, the primary with a cylindrical shape, the secondary smaller and more sharped, and a little punch (Figure 6).

Figure 6 - The end-effector inspired to tension-secured shearing technique.

The cylindrical roller is attached directly to the robotic arm body. The secondary is composed of a little damper hinged to the primary. In this way, it is possible to rotate the second arm to the main one. The two bodies are also connected by a torsional spring to allow the second part to return to its resting position. The relative movements of the two rollers thus allow replicating the technique described above. Instead, the little punch is designed to consolidate prepregs in high curvature surface parts (Figure 7).

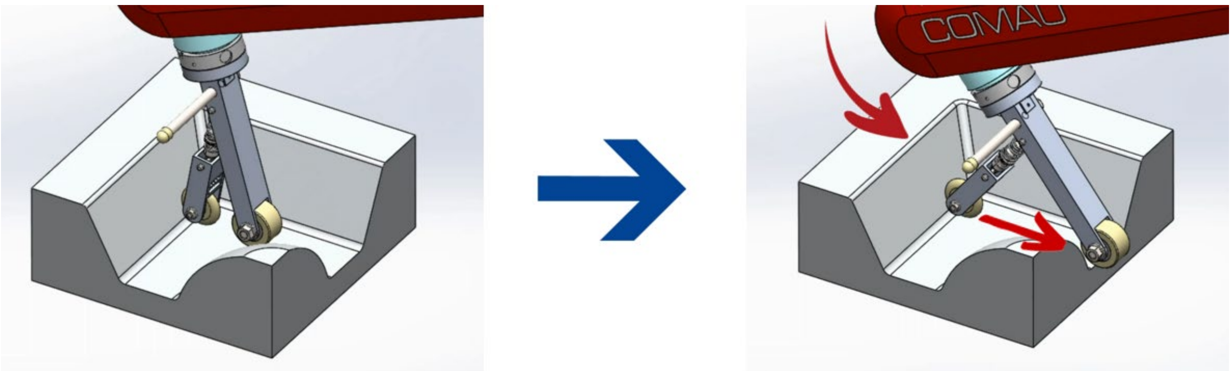

Figure 7 - Representation of the end-effector movements: by inclining the end-effector, the secondary wheel is allowed to rotate from the primary in order to apply tension between the wheels.

Conclusions

Taking into account what has been detailed above, the following conclusion can be written:

- The simulations and tests carried out in a virtual environment have shown that the work done for the discretization of the surfaces has given to the management of the movements of the robotic arm a powerful tool to make the robot automatically follow the course of the surface to be processed, dynamically varying the angle of the end-effector with respect to the shape of the trajectory followed.
- The management of the position of the end-effector is able to automatically follow the trend of the surface to be machined, varying the end-effector angle dynamically with the respect to the shape of the followed trajectory.
- A new effective end-effector has been designed that allows the robotic arm to replicate one of the most used manual techniques performed by the operator on a complex mold, namely tension-secured shearing.

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