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Feasibility study of robotic fibre placement on intersecting multi-axial revolution surfaces

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ABSTRACT

In this paper, the first steps towards using a robotic workcell for the automated fibre placement (AFP) manufacturing of Y-shaped tubes are proposed. The proposed workcell is constituted of a standard serial manipulator holding the fibre placement toolhead combined to a rotary table on which the part where the fibres must be laid out is attached. The investigations carried out in this work explore the feasibility of this setup and more precisely the path planning aspect. To this aim two novel path planning algorithms are presented generalizing the techniques proposed in the literature for open-contoured and cylindrical surfaces. In the first, the maximal geodesic curvature typically allowed in AFP is disregarded to generate continuous paths with a constant placement angle on the branches without any gaps or overlaps. Subsequently, a second algorithm, taking into account this curvature constraint, is presented. These algorithms were implemented in a software using the MATLAB™ suite. Finally, an algorithm to optimize the motion of the robotic system is presented and simulations are discussed.

1. Introduction

Automated Tape Laying (ATL) and Automated Fibre Placement (AFP) are two of the most common automated processes used to produce laminate composite structures. They both rely on the application of continuous carbon or glass fibres, pre-impregnated with a polymer resin (prepreg) onto the surface of a mould. Once the lay-down is complete, the part is placed in a vacuum bag and cured in an autoclave to complete the polymerization of the resin. A comprehensive review of the history of these technologies and the ongoing trends can be found in [1]. While ATL is capable of bringing accuracy and repeatability to the lay-down process and of reaching high deposition rates by delivering wide prepreg tapes (70 mm to 300 mm), it can barely deal with curved surfaces. AFP on the other hand has been developed to overcome this weakness. Indeed, instead of laying down wide prepreg tapes, the placement head of an AFP system is capable of delivering up to 32 narrow tows side by side simultaneously. The tow tensions, feeding speeds, and cut locations are controlled independently, allowing for the delivery of the material along curved trajectories and therefore, production of contoured surfaces.

Because of the large range of applications and sensitivity on manufacturing parameters of composites structures, path planning of the AFP toolhead is a critical aspect to produce a reliable and high performance final product. Many efforts were reported in the literature dealing with the path planning on open contoured surfaces, e.g. [2–5]. A commonly found methodology consists in the definition of a reference curve on the mould surface which is subsequently shifted to produce the different courses composing the ply. The computation of this reference course is usually done by intersecting a reference plane with the mould surface [2,6,7], mapping a 2D curve onto it [8,9], or by using parametric functions [10]. This last method seems to be the preferred technique to produce variable stiffness composites in which the courses are intentionally curved to obtain anisotropic mechanical properties [11].

Once this first curve is defined, it can be shifted along the direction of a defined axis to generate the remaining courses [12]. While this method allows to control the shape of each course quite well, it cannot produce perfectly parallel trajectories in all cases, which may yield gaps and overlaps in the ply. These defects are often unacceptable. To solve this issue, it has been proposed to define the courses such that they remain parallel to each other, see for instance [13]. To this aim, once the reference curve is known, the next course is computed by offsetting the original one of a constant magnitude in a direction locally perpendicular to the curve. It was shown in [2] that this method allows

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to produce a uniform lay-up on open contoured surfaces without any gaps or overlaps.

A common denominator of all the aforementioned works is the fact that they deal with open-contoured or simple closed surfaces such as cylinders and cones. However, many practical parts with more complex geometries would also benefit from being built using AFP. Although, there is obviously a limit on the complexity that this method can handle, the purpose of this work is to demonstrate the possibility of manufacturing a complex structure such as Y shapes using AFP. To achieve this goal it is proposed to use a 7 degree-of-freedom (DOF) robotic workcell including a 6-DOF serial manipulator holding the toolhead synchronized with a 1-DOF rotary table. This system is selected to have a better dexterity and reach than existing AFP machines thereby allowing to produce complex multi-axial composite structures.

The analysis proposed here begins in Section 2 with a definition of the parts considered in this work and the presentation of a segmentation method. Then, in Section 3, the different path generation algorithms considered are described and compared. Finally, simulations of the workcell are discussed in Section 4.

2. Segmentation

While defining tool paths on plates can be done by relatively simple techniques, it can become a much more intricate problem when working on complex 3D surfaces. To handle this complexity, a segmentation strategy is generally used to divide the whole part into simpler regions on which basic path planning algorithms can be applied. The parts considered in this work are assumed to be multi-axial closed surfaces or, more precisely, Y-shaped tubes with circular cross sections. Since they cannot be represented by a single parametric equation, it is assumed that a triangulated mesh of these parts with sufficient resolution is available. This assumption is not restrictive since a great number of CAD software can generate such files. They can even be obtained by 3D scanning. If the shape of the part to cover is exactly known, one could also use other parametric representations of this part (e.g. NURBS) to generate the coverage trajectories and possibly, alleviate the burden of segmenting the 3D model. However, assuming a meshed model of the part is more general and thus, was used in this work. Subsequently, with only limited knowledge of the shape at hand, segmenting appears essential to identify its geometry. Two hypotheses are considered for this segmentation, namely: all the branches of the part have the same diameter, and all the axes of these branches intersect in a common point (cf. Fig. 1.) In the examples illustrating this paper, the geometry of the part was chosen as follows: a diameter of 45 mm, a length of the lower branch (A) of 200 mm and 120 mm for the upper ones (B and C), an angle between the upper branches between 80° and 150°, and a minimal allowed curvature radius of the tow of 635 mm.

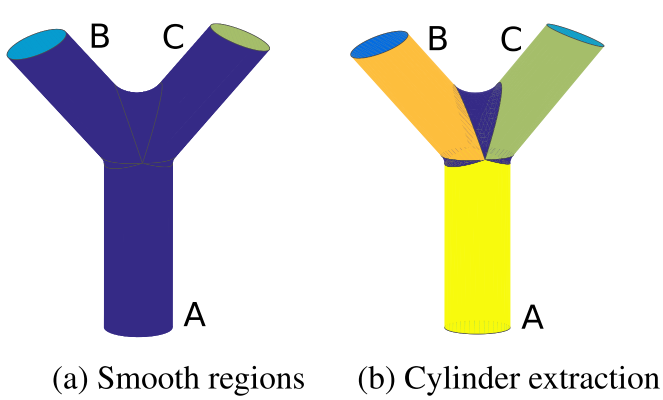

Fig. 1. Segmentation of the part (each color indicates a different region as detected by the algorithm). (a) Smooth regions. (b) Cylinder extraction. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

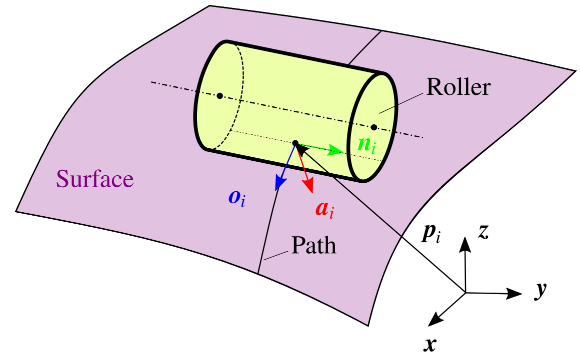

Fig. 2. Local reference frame.

To ensure proper adherence of the fibres to the part, the orientation of the compaction force exerted by the roller used in the toolhead should be kept normal to the mould surface at all time. Moreover, the axis of rotation of the roller has to be inside a plane perpendicular to the trajectory. Based on these constraints, a local reference frame can be constructed for each position along the path of the tool (see Fig. 2.) This frame can be decomposed into three perpendicular unit vectors: $\boldsymbol{a}_i$, the approach inward-pointing vector normal to the surface at the contact point $\boldsymbol{p}_i$, $\boldsymbol{o}_i$ the orientation vector tangent to the path and belonging to the tangent plane of the surface, and finally, $\boldsymbol{n}_i$ the normal vector obtained by: $\boldsymbol{n}_i = \boldsymbol{o}_i \times \boldsymbol{a}_i$. The frame defined as such can be used to obtain the pose of the roller with a 4×4 homogeneous transformation matrix (HTM): $\boldsymbol{P}_i = \begin{bmatrix} \boldsymbol{n}_i & \boldsymbol{o}_i & \boldsymbol{a}_i & \boldsymbol{p}_i \\ & \boldsymbol{0} & & 1 \end{bmatrix}$.

2.1. Segmentation in smooth regions

To define the homogeneous matrix characterizing the pose of the roller, the normals of the surface at any point of the trajectory must be obtained. However, in a triangulated approximation of a real geometry, only the normals of the triangular facets are available. It is therefore necessary to interpolate some of these vectors. To this aim, several methods exist. For instance, in [14] a method was proposed to accurately compute the normal vectors at any vertices of a triangulated mesh regardless of the tessellation. The algorithm proposed in this reference relies on a weighted average of the neighbouring faces' normal vectors. The weight of each of these vectors is computed as the angle between the edges of the faces incident to the considered vertex. This method has been demonstrated to produce robust estimates by many in the literature including the authors [15]. Once the normal vectors at any vertices of the mesh are known, it is also possible to similarly interpolate them to find the normal vector at any point of a facet.

To proceed with the actual segmentation of the part into smooth regions, several algorithms have also been proposed in the literature, e.g. [16,17]. However, considering the assumptions made here, the surfaces dealt with in this work can be handled much more simply. Indeed, since our parts are constituted by intersecting cylinders, segmentation can be done by clustering neighbouring faces separated by an angle lower than a chosen threshold (see Fig. 1a for an example.) The angle between two facets is defined here by the angle between the normals of these two facets. In order to create a new region, a facet is chosen randomly among those which do not belong to an existing region, namely an identified geometrical artefact (a cylinder or the junction.) This initial facet, refers to as the seed facet, is grown into a region by adding neighbouring facets. These neighbouring facets are added only if they have an angle (as previously defined, this angle is measured between normals) with the seed facet below a set threshold (20° in the examples illustrated here) and are then concatenated to the