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An accurate approach to roller path generation for robotic fibre placement of free-form surface composites

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ABSTRACT

Due to their high stiffness and strength, composites are widely used in the aerospace industry. To manufacture composites, especially composites of free-form surface structure, process of robotic fibre placement (RFP) is widely used in industry. However, due to the complex geometry of the free-form surface, it is quite challenging to generate accurate roller paths for placing fibre on the surface for high composites quality. To address this problem, this work proposes an accurate roller path planning method using the differential geometry. The roller paths can ensure the specified small gaps and overlaps between two tows for high composite quality. This approach is applied to several examples, and their results verify the validity of this approach. It has great potential to be adopted in industry.

1. Introduction

Composites are being intensively used as structural components in the aircraft and aerospace industries mainly because of their excellent fatigue performance along with their high strength-to-weight and high stiffness-to-weight ratios [1,2]. Furthermore, their thermal characteristics allowed the design of high precision instruments with negligible thermal expansion coefficients. High creep resistance and low-moisture absorption give excellent dimensional stability and extend the use of composites in a variety of consumer and industrial products.

Several different manufacturing processes were developed for the fabrication of composite structures [3], and on-line consolidation is one of the feasible processes. It can be described as a composite manufacturing technique, where resin impregnated fibre tows are simultaneously laid, heated, consolidated and cured in a single step [4]. Manual on-line consolidation is performed by manually placing and compressing the materials on the mould, which is the oldest and simplest form of on-line consolidation. When integrated with a computer-controlled system, the on-line consolidation can be fully automated, which leads to further cost savings in fabrication by increasing productivity and reducing labour cost [5]. Particularly, automated tape laying (ATL), filament winding (FW) and RFP are three typical techniques of automated on-line consolidation.

ATL process provides the required repeatability and accuracy for manufacturing the composite structure. The fabrication technique resembles manual lay-up to a great extent but the automation of the mechanism is achieved by a well-controlled consolidation head, moved and oriented by a multi-axis machine [6]. Although direct labour costs are greatly reduced and the efficiency is dramatically increased, the mechanism lacks the ability to manufacture a wide range of three-dimensional structures and to generate several desired surface patterns.

FW is an another automated process, where the fabrication of the composite structure can be achieved with the on-line consolidation technique. The continuous tows are unwound from the spool mounted on a tensioner and then wound again around a rotating mandrel [7]. Filament winding suffers from the limitations on the feasibility of certain geometrical structures and pattern designs. Structures are generated by winding the tows around the mandrel and consequently flat panels, multiple axis bodies or complex surfaces are not possible.

RFP is the only feasible automated on-line consolidation process to fabricate complex-shaped three-dimensional composite structures to date. This technique uses a placement head in conjunction with a robot manipulator to produce the composite structure with impregnated tows [1]. It is capable of achieving all desired tow orientations and patterns in the different layers of the generated product [8]. RFP offers many important features and advantages, including cutting and restarting the tows, debulking and consolidation of the material in situ, and high degree of repeatability. Furthermore, the utilisation of a robot manipulator increases the flexibility of the manufacturing process and allows for the fabrication of complex structures [9,10].

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In a similar manner to Computer Numerical Control (CNC) machining, the placement head guide the roller to lay down each course along the formulated paths. That is to say, the accuracy of roller paths will influence the quality of the final product. Therefore, this paper aims to develop an algorithm to generate roller paths more exactly, with minimal gaps or overlaps between adjacent tows.

The rest of the paper is organised as follows: the next section reviews related literature; Section 3 analyses RFP process; Section 4 describes the overall methodology of RFP path planning; Section 5 presents the components of the path planning method, including roller position and orientation determination, initial path construction, RFP path offset and roller location determination; Section 6 illustrates the simulation results of the proposed method; and Section 7 provides the paper's conclusion.

2. Literature review

Path planning for robotic fibre placement has been widely studied, and some achievements are already obtained in this field. Shirinzadeh et al. [11] proposed a path planning algorithm for open-contoured structures, entitled the surface curve algorithm for robotic fibre placement. This algorithm formulates a set of paths by offsetting surface curves. In their algorithm, the offset distance remains always the same for generating each path. There is no doubt about the application for plane mould. However, once the mould becomes a curved surface, keeping a constant offset distance could not guarantee all the tows being placed on the mould completely. In other words, the offset distance must be calculated for offsetting each path. Gurdal et al. [12] mainly discussed the fabrication issues encountered during the manufacture of tow-steered laminates. During the structural fabrication phase, gaps and/or overlaps are generated between neighbouring tow courses, which must be adequately considered. Thus, a coverage parameter and an interweaving technique are introduced to diminish the effect of the gaps. Similarly, the interweaving technique applied to plies that permit overlaps instead of tow-dropping is shown to smooth out the thickness variation that occurs due to the extra plies within the overlap regions. As far as Schueler et al. [13] concerned, a design and analysis tool for fibre placed composites must be capable of modelling the part down to the level of the tow, in turn requiring a method to represent the position of individual tows on the design surface. In order to meet the requirements, they proposed two methods to represent individual tows in a fibre placed part. The former approximates offset curves on a free-form surface using the geometric constraints of the fibre placement process. The latter approximates a curve on a free-form surface that can be used to generate a laminate family ply. Both of the approximation methods are demonstrated to be sufficient for the accuracy of fibre placement. Sturges et al. [14] developed a compliance model to ensure the most accurate path planning in the absence of external position feedback means, which is one design aspect for the automation of the on-line consolidation fibre placement task. To streamline all aspects of design, analysis and manufacturing, Schueler and Hale [15] presented an integrated design and analysis system for use in preliminary through detailed design phase of a fibre placed structure, which is called Steered Composites Analysis and Design System (SCADS). This system is unique in that it controls the design of tows rather than plies, and as such enables an evaluation of manufacturability during preliminary design phase, without the use of proprietary machine programming systems. Shirinzadeh et al. [16] described the overall strategy for the establishment of a flexible robotic fibre placement technique. In their work, three different types of fibre placement for open surfaces are discussed. These include simulation-based fibre path generation, fibre steering and sensory-based contour following methodologies. By the implementation on flat or contoured surfaces, the first methodology is demonstrated to be the most systematic and flexible one from implementation and type of surfaces points of view.

In short, the majority of the path planning studies regards the offset distance as a constant value. The consideration of varied offset distance is not included. Rare are the methods necessary to guarantee all the tows being placed on the mould completely. Besides, most of the developed methods do not take roller location determination into account, which allows a smooth roller motion along the generated path.

3. Analysis of the RFP process

The RFP process discussed in this paper can be represented by increasing levels of abstraction. At the lowest level is the tow, and this is the basic abstraction considered within design and analysis. The tow itself consists of thousands of hair-like fibres aligned along the length of the tow and impregnated with resin. It is usually 3.175 mm wide and 0.25 mm thick. When cured with heat and pressure, the resin impregnated tow imparts strength and stiffness along its length. A placement head delivers from one up to 30 adjacent tows in a single pass. The adjacent tows in a single pass are known as a course. Multiple courses are placed alongside each other to form a single layer, known as a ply. Multiple plies are placed atop each other to impart thickness to the structure, regarded as a part [13]. The levels of abstraction are illustrated in Fig. 1.

Fig. 2 shows a possible configuration of the RFP system. A placement head, manipulated by a 6-dof robot, is able to provide

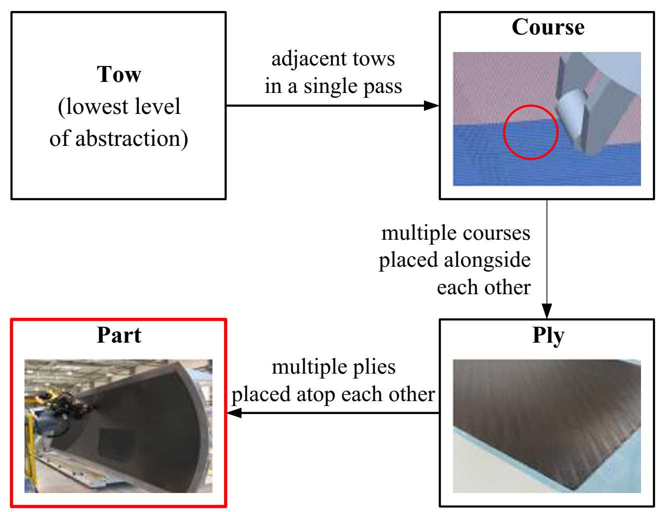

Fig. 1. Levels of abstraction in the RFP process [17–19].

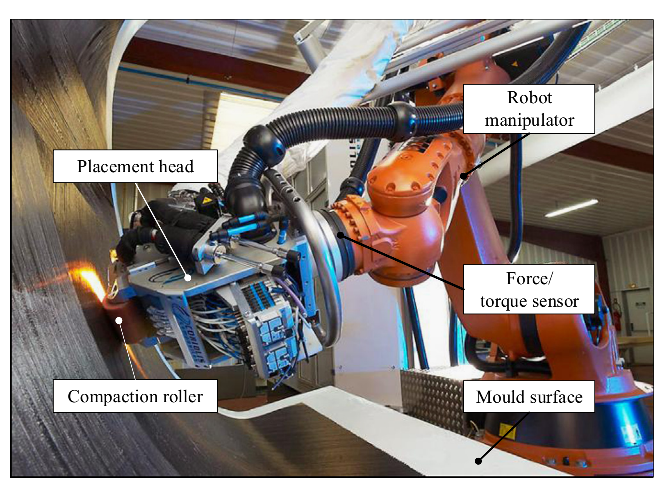

Fig. 2. A possible configuration of the RFP system [20].