Developing a Trajectory Planning for Curved-Contoured Surfaces for Use by 8-DoF Workcell in Robotic Fibre Placement

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Abstract. The replacement rate of conventional material by composites is increasing. Possessing high specific strength and stiffness makes composites attractive to many applications. Different techniques are being utilized for composite placement processes. Robotic Fibre Placement (RFP) is introduced as a competing approach for composite fabrication. This approach can provide many advantages; e.g. low labor cost, high performance, quick and effective process. The current work proposes an 8-DoF system established for laying the composite material. This system composed of three main units includes a 6-DoF industrial robot and two mandrel tools with different configurations. A sensory-based feedback control system is developed to manage the placement process. The placement process can be performed on two different surfaces. The end-cap surface has been fabricated then the cylindrical surface. Different geometries of pressure vessels have been generated; e.g. Oxidizer tanks that can be used in many applications such as (Hybrid rockets).

1. Introduction

Recently, composites have gained popularity as an alternative material in many industrial sectors because of their excellent properties [1-4]. Fibrous composites are the mostly used composites in many applications, especially in the aerospace industry. Carbon fibre reinforced polymers (CFRP) became one of the most significant fibrous composites after the growth of applications and experience in this field because of their superior performance [5, 6].

Composite lay-up is one of the most important challenges facing the wider use of composite products. There are many traditional techniques of manufacturing composite structures such as hand lay-up and tape laying [7, 8]. Those techniques are using a manual placement of both fibre and matrix materials on a fabricated mold with the required geometry. They have many drawbacks such as time-consuming, hazardous, labor-intensive, and low efficiency, which result in a high material scrap rate [9]. Therefore, the conventional methods may be combined with the computer-controlled systems, whereas online consolidation was automated carefully to obtain accurate products. Accordingly, three techniques of automated consolidation are being used, Automated Tape Laying (ATL), Filament Winding (FW) and Robotic Fibre Placement (RFP) [10, 11]. RFP is introduced as innovative techniques that can overcome most drawbacks of conventional techniques, as it can satisfy all current in-
dustry requirements. Applying this procedure in the industry can provide cost-effective, high flexibility, faster and highly accurate process. Hence, it can be used for all intricate structures [9, 12-15].

Many research works have been done on different techniques of fibre placement. Sofi et al. [16] established a review of the dry fibre winding processes. Different winding techniques were explored according to the application geometry, e.g. geodesic and non-geodesic formulations. The review introduced some innovative strategies for fibre path planning in the upcoming research work. However, the authors pointed out there still are some challenges to apply their strategies on complex shapes. Rousseau et al. [17] outlined another review about the multiple lay-up techniques that were performed for Automated Fibre Placement (AFP) processes. Different lay-up strategies were described using the numerical and mathematical work of the fibre placement on the conical, cylindrical, curved, planer and perforated planer surfaces.

Shirinzadeh et al. [9] outlined the procedure of the RFP process. Three different methods were described, including fibre path generation based on simulation, fibre steering, and sensory-based contour. A straight line and a circular arc trajectory were used for the fibre placement process on flat and complex surfaces. Their work has been extended on RFP process in [18]. An automatic fibre path was generated using an innovative algorithm, which was applied for opened and closed surfaces. Another path generation on open-contoured structures using a surface curve algorithm (SCAR), has been shown in [19]. The proposed methods were conducted to produce a set of curved and flat surfaces to ensure that the RFP paths of the lamina were smooth without any drawbacks. Another path planning technique for the compaction roller on different geometries has been produced in [13]. The proposed technique was used for free-form shaped structures. The path planning research has been continued for more complex structures. For example, Hely et al. [20] used a robotic fibre placement system to manufacture Y-shaped tubes. Hassan et al. [21] performed another fibre placement process for a dome-shaped surface, using multiple Autonomous Industrial Robots (AIRs). Zhao et al. [22] also presented an approach for path planning but for the aircraft tail using AFP.

Based on the review, most of the path planning work was for the open contoured surfaces. No experimental work has been done for manufacturing pressure vessels using RFP, especially the closed surfaces with extreme curvatures. Therefore, the present work proposes a novel technique which aims to use RFP to fabricate the cylindrical pressure vessels, e.g. the oxidizer tank which can be included in many implementations such as (Hybrid rockets). An 8-DOF workcell is established to perform the placement process. It is including an industrial robot which is connected to two, horizontal and vertical, mandrel tools. Path planning algorithm is constructed for the proposed surfaces. Also, a force/torque feedback system is utilized to control the path generation process. The following sections will outline the proposed process in-details.

2. Sensory based lay-up
The direction of fibre placement plays an important role in calculating the final mechanical properties of the composite products. To obtain the accurate lay-up angles, a suitable trajectory for the robot end-effector should be generated. The current work is proposing a path generation method that uses a sensory-based feedback control system. The robot trajectories are produced based on a real-time process. This method utilizes the information of sensory-based feedback signals to define the tag points which are generated to define the placement trajectory. A 6-DoF force/ torque sensor is installed in the robot head to monitor the compaction force for the placement process. The compaction force is a vital aspect for ensuring the best consolidation of the fibre tows on the substrate surfaces. The end-effector trajectory is corrected using the collected data to maintain the same value of the compaction force between the robot head and the workpiece surface. This force is also adjusted to be normal on the workpiece surface during the whole process based on the proposed algorithm in [9]. This technique doesn't need any mathematical model as the end-effector direction is adjusted to be always normal to the structure surface. The data of the force/torque sensor is compared with the determined values to calculate the exact angle between the end-effector and the surface normal, based on the relationship developed in
Finally, after generating the correct paths, application programs are written to define all placement paths. Then the generated programs are uploaded to the robot controller using the robot software.

3. Experimental setup
The lay-up procedure is performed based on a synchronized motion between the robot end-effector and the workpiece surface. We established an innovative workcell which composes of three main units to obtain the accurate motion. The first unit is a fibre placement head which is operated with a 6-DoF industrial robot (Yaskawa Motoman SK120) as shown in Fig. 1. Prepreg tows for the fibrous composite have been used in this work. The tow motion occurs throw the creel rollers system until reaching the compaction roller.

Fig. 2a. presents the second unit (Vertical mandrel tool) which is used to manufacture the end-cap surface of the cylindrical pressure vessel. A cylindrical tool is moved by a servo-motor using a gear system. The motor motion is controlled by feedback signals using a PCI controller card. The motor position, velocity, and acceleration are controlled based on the end-effector motion. Fig. 2b. shows the third unit (Horizontal mandrel tool). The presented system is used to perform fibre placement on the circumferential surface of the pressure vessel. The lay-up on that surface is applied with different angles, that will be described in Section 4. The servo motor is also controlled using feedback signals from the motor encoder to the robot main control unit.

![Figure 1. Robotic fibre placement facility (SK120).](image1)

(a) Vertical mandrel tool.  (b) Horizontal mandrel tool.

![Figure 2. Mandrel tools.](image2)
4. Results and discussion

4.1. Generated trajectories

Offline programming is used to manage the workcell operation in the placement process. Robot application programs are created based on the required path directions. An operation algorithm is used for each required placement angle as presented in Fig. 3. Therefore, the fibre placement on the cylindrical pressure vessel surface has been obtained based on two stages. Firstly, the circumferential surface of the pressure vessel has been fabricated using four different trajectories as presented in Fig. 4. Fig. 4a. shows fibre placement on 0° angle. The robot end-effector is moved in a longitudinal direction to the endpoint of the path. Subsequently, during return time, the mandrel tool is rotated with a defined angle according to the width of prepreg tows. Figs. 4b. and 4c depict the paths of 45° and -45° angles, respectively. The end-effector is moved in an inclined angle with the slow rotation of the cylindrical tool to produce the required paths. Finally, Fig. 4d. shows the trajectory obtained of 90° angle. The end-effector is moved to the start point, then the mandrel tool revolved continuously until the end of the process.

![Path generation algorithm](image)

**Figure 3.** Path generation algorithm.
Secondly, the end-cap part is fabricated based on one predefined trajectory as shown in Fig. 5. The robot head is moved in a series of linear and spline motions until finishing the first increment. Subsequently, the mandrel tool revolved using step motion during the return time of the end-effector.

![End-effector Direction](image1)
![End-effector Direction](image2)
![End-effector Direction](image3)
![End-effector Direction](image4)

(a) 0°  (b) 45°  (c) -45°  (d) 90°

Figure 4. Circumferential surface placement.

Figure 5. End-cap placement.

Figure 6. Circumferential surface placement.

4.2. RFP products

The proposed operation is applied using thermosetting composite prepreg tows. A uni-direction carbon fibre prepreg tows (T700G) from Toray America, Inc is used. A lay-up of eight-layer with four different directions is applied on the cylindrical surface. In addition, four-layers on the end-cap surface are obtained. Then, the workpiece is cured in an oven with controlled pressure and temperature to generate the final product. Fig. 6. shows the final product after the curing process.

5. Conclusion

Composites have become an important component for aerospace sector due to its superior properties. Robotic fibre placement technique is extensively used to fabricate composite structures with high accuracy. The current work proposed an effective technique for fabricating a pressure vessel. This technique is based on an 8-DoF workcell. A 6-DoF robot is combined with two different mandrel tools to fabricate the pressure vessel surfaces. The robot end-effector trajectories are calculated based on a feedback control system. The workpiece is then cured to get the final product. The proposed technique has the potential to fabricate the oxidizer tank which can be applied in different applications, e.g. (Hybrid rocketed). In future work, the two parts of the pressure vessel will be fabricated using the robot operated with only one mandrel tool. A 2-DoF mandrel tool will be built to lay-up the composite material on the whole structure.
References
[1] S. Taj, M. A. Munawar, and S. Khan, “Natural fiber-reinforced polymer composites,” *Proceedings-Pakistan Academy of Sciences*, vol. 44, no. 2, pp. 129, 2007.
[2] R. M. Jones, *Mechanics of composite materials*: CRC press, 2014.
[3] P. Zhao, B. Shirinzadeh, Y. Shi, S. Cheuk, and L. Clark, “Improved uniform degree of multilayer interlaminar bonding strength for composite laminate,” *Journal of Reinforced Plastics and Composites*, vol. 36, no. 17, pp. 1211-1224, 2017.
[4] G. Mittal, K. Y. Rhee, V. Mišković-Stanković, and D. Hui, “Reinforcements in multi-scale polymer composites: Processing, properties, and applications,” *Composites Part B: Engineering*, vol. 138, pp. 122-139, 2018.
[5] C. Soutis, “Carbon fiber reinforced plastics in aircraft construction,” *Materials Science and Engineering: A*, vol. 412, no. 1-2, pp. 171-176, 2005.
[6] L. Pehlivan, and C. Baykasoğlu, “An experimental study on the compressive response of CFRP honeycombs with various cell configurations,” *Composites Part B: Engineering*, vol. 162, pp. 653-661, 2019.
[7] C. Grant, “Automated processes for composite aircraft structure,” *Industrial Robot: An International Journal*, vol. 33, no. 2, pp. 117-121, 2006.
[8] Z. Gurdal, B. Tatting, and K. Wu, "Tow-placement technology and fabrication issues for laminated composite structures." p. 2017.
[9] B. Shirinzadeh, G. Alici, C. W. Foong, and G. Cassidy, “Fabrication process of open surfaces by robotic fibre placement,” *Robotics and Computer-Integrated Manufacturing*, vol. 20, no. 1, pp. 17-28, 2004.
[10] F. Bullock, S. Kowalski, and R. Young, “Automated prepreg tow placement for composite structures,” *Advanced materials: The challenge for the next decade.*, vol. 1, pp. 734-745, 1990.
[11] M. N. Grimshaw, C. G. Grant, and J. M. L. Diaz, "Advanced technology tape laying for affordable manufacturing of large composite structures." pp. 2484-2494.
[12] T. Aized, and B. Shirinzadeh, “Robotic fiber placement process analysis and optimization using response surface method,” *The International Journal of Advanced Manufacturing Technology*, vol. 55, no. 1-4, pp. 393-404, 2010.
[13] L. Yan, Z. C. Chen, Y. Shi, and R. Mo, “An accurate approach to roller path generation for robotic fibre placement of free-form surface composites,” *Robotics and Computer-Integrated Manufacturing*, vol. 30, no. 3, pp. 277-286, 2014.
[14] G. Alici, B. Shirinzadeh, A. McConville, C. W. Foong, and M. Ang, “A mathematical model for a pneumatically actuated robotic fibre placement system,” *Robotica*, vol. 20, no. 5, pp. 545-551, 2002.
[15] P. Zhao, B. Shirinzadeh, Y. Shi, S. Cheuk, and L. Clark, “Multi-pass layup process for thermoplastic composites using robotic fiber placement,” *Robotics and Computer-Integrated Manufacturing*, vol. 49, pp. 277-284, 2018.
[16] T. Sofi, S. Neunkirchen, and R. Schledzewski, “Path calculation, technology and opportunities in dry fiber winding: a review,” *Advanced Manufacturing: Polymer & Composites Science*, vol. 4, no. 3, pp. 57-72, 2018.
[17] G. Rousseau, R. Wehbe, J. Halbritter, and R. Harik, “Automated Fiber Placement Path Planning: A state-of-the-art review,” *Computer-Aided Design and Applications*, vol. 16, no. 2, pp. 172-203, 2018.
[18] B. Shirinzadeh, C. Wei Foong, and B. Hui Tan, “Robotic fibre placement process planning and control,” *Assembly Automation*, vol. 20, no. 4, pp. 313-320, 2000.
[19] B. Shirinzadeh, G. Cassidy, D. Oetomo, G. Alici, and M. H. Ang Jr, “Trajectory generation for open-contoured structures in robotic fibre placement,” *Robotics and Computer-Integrated Manufacturing*, vol. 23, no. 4, pp. 380-394, 2007.
[20] C. Hély, L. Birglen, and W.-F. Xie, “Feasibility study of robotic fibre placement on intersecting multi-axial revolution surfaces,” Robotics and Computer-Integrated Manufacturing, vol. 48, pp. 73-79, 2017.

[21] M. Hassan, D. Liu, and D. Xu, “A Two-Stage Approach to Collaborative Fiber Placement through Coordination of Multiple Autonomous Industrial Robots,” Journal of Intelligent & Robotic Systems, vol. 95, no. 3-4, pp. 915-933, 2018.

[22] Y. Zhao, Z. Han, Y. Zhang, and H. Fu, “Path Planning and Post-processing Algorithm for Fiber Placement of the Aircraft Tail.” pp. 96-99.