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SPATIAL AND FUNCTIONAL CONTROL OF EXTRUSION HEAD FOR ADDITIVE MANUFACTURING OF CONTINUOUS FIBRE REINFORCED POLYMER COMPOSITES USING 6-AXIS ROBOTIC ARM

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Abstract— This paper addresses the challenges of additive manufacturing (AM) of continuous fibres on non-planar surfaces using 6-axis robotic arms. Two ABB IRB 1200 robots (controlled by an IRC5 controller) are utilized with a custom-designed material extrusion head that is controlled by Duet 3 Main Board. For toolpath planning, a workflow is developed in Grasshopper. The developed toolpath planning interface generates G-code for fibre extrusion lengths and other process-driven functions. Simultaneously, RAPID code is generated for robot movements. Synchronization between the robot movements and the material extrusion head is achieved by integrating G-code lines in the RAPID code. A user-friendly application programming interface (API) was developed in-house to manage communication signals between the robot and material extrusion head controller. The working system is demonstrated by depositing curves of continuous fibre on planar and non-planar (doubly curved) surfaces.

Keywords- additive manufacturing; multi-DOF fabrication; toolpath planning; continuous fibre; robotic arm synchronization

I. INTRODUCTION

Additive Manufacturing (AM) of continuous fibre-reinforced polymer composites (cFRPCs) by means of material extrusion (MEX) has potential to significantly expand the design space of composite structures. However, the anisotropic nature of fibre reinforced materials means that the mechanical properties produced from them are sensitive to fibre paths. As a result, the layer-by-layer approaches usually employed for isotropic materials are not ideal for cFRPCs. Recently, research and development into technologies that enable precise control of fibre placement in AM processes through the use of multi-axis robots has gained attention [1-6]. Yet, combining extrusion heads for continuous fibre polymer composites with industrial 6-axis robot is not trivial and requires understanding of the material, process, and automation.

Challenges that are addressed in this work include:

a) Toolpath planning in 3D using a 6-axis robot
b) Development of an extrusion head for continuous fibres
c) Synchronization of the spatial position of the robot with the actions of the extrusion head

Unlike neat polymer printing that uses the layer-by-layer conventional slicing approach, continuous fibre printing requires true 3D tool pathing. True 3D tool pathing enables fibres to be deposited along stress lines to fully exploit the strength and stiffness of the continuous fibres. Introducing doubly curved surfaces to the additive manufacturing platform introduces challenges in spatial orientation of the extrusion head related to the printing bed. Since the Tool Center Point (TCP), i.e. nozzle tip, should align with the surface normals along the path. To address these challenges using a gantry system, complicated engineering modifications (like installing and controlling multiple external axis) are required. However, a 6-axis robotic arm can provide a convenient solution for AM on doubly curved surfaces.

Toolpath planning for non-planar AM using 6-axis robots necessitates increasing the number of variables required to specify fibre path. Unlike 3-axis printers that are controlled by G-code with predefined XYZ coordinates of the path, AM using a robotic arm mandates the correct orientation of the tool, i.e., the extrusion head, to align with the normal to the surface at each path point. Consequently, this requires complex maneuvering of the robot and presents a collision hazard between the extrusion head and the printing bed or the printed structure. In this paper, a toolpath planning workflow is developed in Rhino-Grasshopper. Pre- and post- toolpath segments are added to the desired fibre-path to facilitate initial adhesion of fibre tow to the printing bed and avoid collision of the extrusion head.

In contrast to the polymer extrusion process where molten polymer is forced through a die using pressure, continuous fibre extrusion demands precise control over the fibre length. Over-extrusion can lead to fibre buckling within the nozzle, resulting in jamming, while under-extrusion can result in high stress concentrations in the fibres at the nozzle tip, along with significant tension in the fibre feed system, which may ultimately cause the printed fibre tow to detach from the printing bed. Hence, the toolpath planning workflow presented in this work discretizes the designed fibre-path into polylines to minimize error accumulation in the fibre feed. The resulting polyline is used to generate G-code for extrusion values and RAPID (Robotics Application Programming Interface for Data) code for ABB robot movements. Both codes are synchronized using a novel approach to realize the actual print using the extrusion head mounted on the robot. Furthermore, AM of cFRPCs introduces new process-based functions like fibre cut. This requires custom design of the extrusion head and synchronization with the robot movements.

Another challenge that accompanies additive manufacturing using 6-axis robot is the restricted user-interface offered by the manufacturers that limits design and function flexibility. This is also associated with the high cost of manufacturers' licenses and subscriptions. For example, ABB Robotstudio offers additive manufacturing PowerPac support for a paid subscription. This motivates the development of affordable in-house communication and synchronization interfaces.

In this work, solutions for the above-mentioned challenges will be addressed and a demonstration of a spatial three-dimensional contours on a double-curved surface will be implemented.

II. HARDWARE

A. Robots

The machinery used in this research consists of two ABB IRB 1200 robots, controlled by an IRC5 controller, and a custom-designed printing head, controlled by a Duet 3 Main Board.

Figure 1 shows the system setup. The robot located on the left is equipped with a custom-designed printing head (mounted on its sixth axis) and a fibre feed (mounted on its base). The robot on the right is responsible for the positioning of the work object. This offers convenient flexibility in positioning the printing bed (work object) within the reach of the tool (printing head) in the workspace.

Figure 1. Machinery and system setup for non-planar printing of continuous fibre using 6-axis robotic arm.

B. Extrusion head

Figure 2 shows a CAD model of the extrusion head used and lists its different components. Several functional components are included to facilitate continuous fibre printing such as: 1) a cutting mechanism, 2) a disengageable fibre feed mechanism, and 3) a magnetic jam detection system to pause

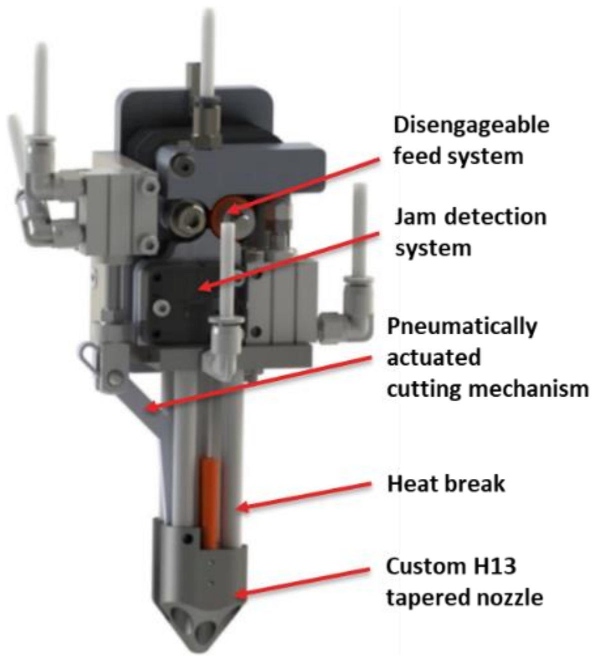


Figure 2. Printing head for material extrusion (MEX) process with continuous fibres. Rendered image of the CAD model, showing different functional components.

the printing operation in case of nozzle jamming or fibre stock runout. The different input and output signals required for actuating the printing head are discussed in Section III.B.1.

III. METHODOLOGY

A. Toolpath planning

1) Path discretization

An interface has been developed in Grasshopper to generate the toolpath for any arbitrary spatial three-dimensional contours on doubly curved surfaces. The desired print (curve) is discretized into polylines that define XYZ coordinates and the fibre extrusion length for each segment. To realize a smooth print and reduce computational power simultaneously, the path is divided into non-equidistant polylines; the lengths of polylines decrease (giving finer discretization of the path) according to the radius of curvature. Figure 3 (left) shows generated polylines for two arbitrary curves. At low radius of curvatures, shorter polylines are generated, in contrast to longer and fewer ones for higher radius of curvatures.

The optimization criteria to achieve a smooth curved print are selected according to two tolerances. The first is an angle tolerance of maximum 45-degrees between the tangent to the curve segment and the corresponding polyline segment. The second is a distance tolerance of 1 mm for the perpendicular to the polyline segment from the midpoint of the curve segment (arc). Although this is beneficial for print quality of highly curved fibre-path, it introduces a challenge in robot motion synchronization with fibre extrusion at the printing head, as extrusion lengths are distinguished for each polyline. This challenge will be addressed in Section III.B.

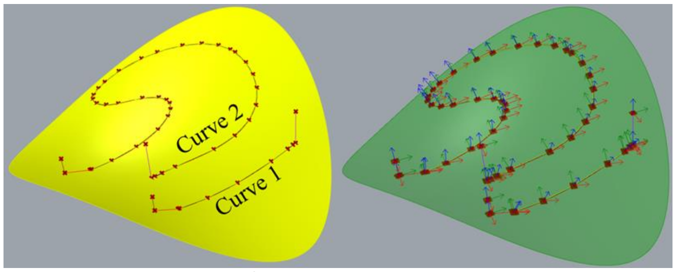


Figure 3. Visualization of the generated non-equidistant polylines with reduced point count for illustration. Toolpath polylines (left). Path frames for robotic arm movements (right); Planes (frames) are tangent to surface at each point and defined by red and green vectors. Their normals as blue vectors.

In addition to XYZ coordinates, spatial three-dimensional prints require the definition of planes tangent to the curved surface so their normals align with the surface normals (see Figure 3 right).

2) Robot movements

Robot movements are defined using a set of subsequential targets by translating the tool center point (TCP) from one frame (plane) to another and aligning the TCP normal with the plane normal. Inverse kinematics were calculated using RobotComponents, a Grasshopper plug-in. Figure 4 shows a nonplanar printing simulation of two curves on a corrugated surface. A simplified printing head is modeled in the simulation. Each frame normal is represented as a vector (in blue). Fine linear robot movements are assigned to translate between successive robot targets.

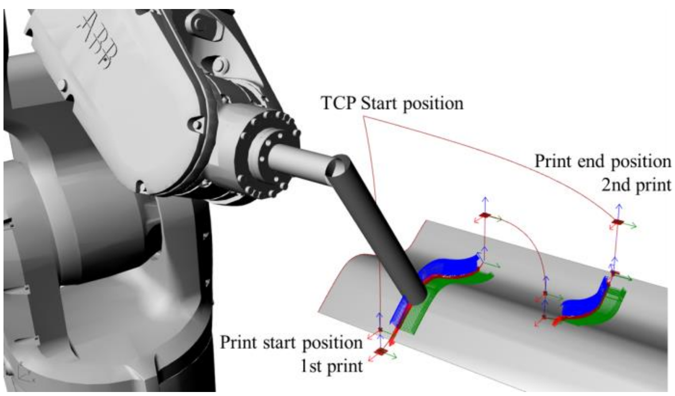


Figure 4. Toolpath visualization and process simulation for a nonplanar printing. A simplified printing head is modeled with an equivalent TCP position and normal.

In addition to fibre-path movements planning for the desired print, additional path segments (pre- and post fibre-path segments) are automatically integrated to the generated path to achieve a smooth print and minimize collision hazard with the curved surface. A ramp-in movement (with 30° angle to the surface) is planned before the fibre-path (illustrated in Figure 3 and Figure 4 in red) to realize a smooth approach of the TCP to the surface, which guarantees initial adhesion of the fibre tow to the printing bed. To avoid collision of the nozzle with the printing bed at the end of the print or during translating from one print's end to start another, a post-fibre-path segment is integrated to provide tool clearance in the Z-direction (illustrated in Figure 4 in red). In Figure 4, fibre-path frames are generated by a fine polyline and illustrated by close frames. Other pre- and post- path frames are represented by individual planes (frames) and red lines connecting them.

B. Synchronization

1) Printing process flowchart

The printing process flowchart is presented in Figure 5. A print starts by moving the robot from its home position to the designated starting position, where it sends a signal to the Duet3D controller to heat up the nozzle. Once the nozzle reaches the set temperature, the robot moves to the starting print position (see Figure 4) and performs the ramp-in movement (refer to in Section III.A.2), followed by executing the designed fibre-path, which is divided into two main sections: pre-cut and post-cut.

During the pre-cut phase, each polyline segment of the robot's movement corresponds to a unique extrusion value (G-code line) from the Duet3D controller, as described in Section III.A.1). The robot pauses at the end of the pre-cut length, waiting for the fibre cutting operation, which is executed by the Duet3D controller using a cut G-code macro. Once the cutting operation is completed, the robot proceeds to execute the post-cut movements without any additional fibre extrusion.

The post-cut path segment is assigned to clear the nozzle from the cut length. Upon completion of the designed fibre-path, the robot moves to the end print position which is offset in the Z-direction, and pauses, ready for the next print.

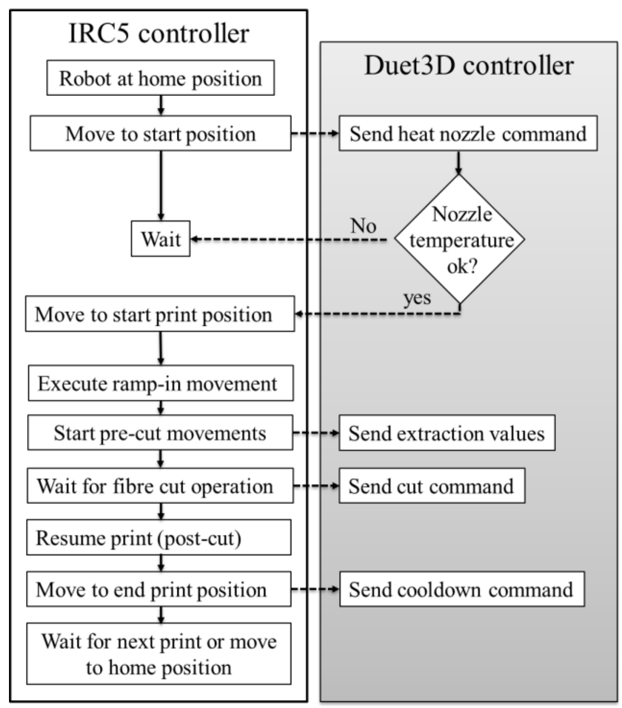


Figure 5. Printing process flowchart and communication signals flow.

Such an interactive process flow (see Figure 5), and thus, two-way continuous communication between the ABB controller (IRC5) and the extrusion head controller (Duet3D) demands a swift and user-friendly synchronization strategy that is intuitive and does not rely on the user's software proficiency.

To this end, a custom CAM data generation workflow and an in-house communication protocol have been developed.

2) *CAM data generation workflow*

The required CAM data for this printing process consists of G-code and RAPID code. G-code is generated for extrusion length values and for the actuation of other functional components in the printing head like cutting mechanism and nozzle heat cartridge. RAPID code is generated for robot movements. Both codes were generated using the same toolpath discretization (polyline). Figure 6 shows a diagram of the CAM data generation workflow.

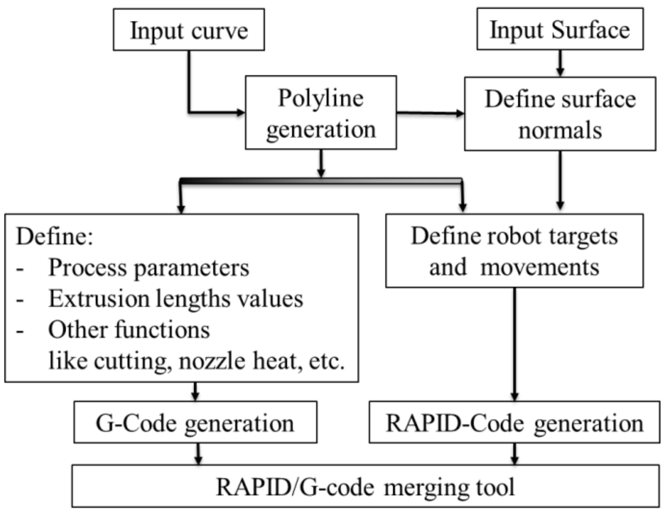
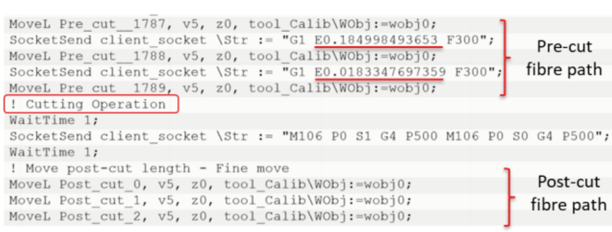


Figure 6. CAM data generation workflow.

In the final stage, after generating both codes, they are merged. G-code lines are automatically integrated in the RAPID code as send string lines. Accurate position of each G-code line depends on the process flowchart (see Figure 5). An example of RAPID code with integrated G-code lines is given in Figure 7. The selected code section shows a cutting operation. Few movement commands for the pre-cut fibre-path are shown with the corresponding extrusion value G-code commands.It is clear how the extrusion value differs for each segment movement according to the polyline length. Fibre feed rate is selected to be 300 mm/min which corresponds to TCP velocity of 5 mm/sec (v5 in RAPID language) by the ABB robot. Following the fibre cut operation are post-cut movements with no further fibre extrusion. During these movements, the fibre cut length is cleared out of the nozzle.



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MoveL Pre_cut__1787, v5, z0, tool_Calib\WObj:=wobj0;
SocketSend client_socket \Str := "G1 E0.184998493653 F300";
MoveL Pre_cut__1788, v5, z0, tool_Calib\WObj:=wobj0;
SocketSend client_socket \Str := "G1 E0.0183347697359 F300";
MoveL Pre_cut__1789, v5, z0, tool_Calib\WObj:=wobj0;
! Cutting Operation
WaitTime 1;
SocketSend client_socket \Str := "M106 P0 S1 G4 P500 M106 P0 S0 G4 P500";
WaitTime 1;
! Move post-cut length - Fine move
MoveL Post_cut_0, v5, z0, tool_Calib\WObj:=wobj0;
MoveL Post_cut_1, v5, z0, tool_Calib\WObj:=wobj0;
MoveL Post_cut_2, v5, z0, tool_Calib\WObj:=wobj0;
```


Figure 7. Example of RAPID code with integrated G-code at a fibre cut operation.

3) *In-house communication protocol*

In pursuit of affordable efficient communication between the IRC5 controller and the Duet3D controller, an in-house application programming interface (API) has been developed in Python to operate on an upper computer (desktop). This API is responsible for managing the communication process between both controllers through socket communication via Transmission Control Protocol (TCP).

A schematic of the developed communication protocol is presented in Figure 8. The communication process starts by uploading the RAPID code (that includes integrated G-code lines) to the ABB robot controller through the API. Subsequently, the RAPID code is executed, and when a G-code line is reached, it is sent as string data to the Duet3D controller via the established socket communication through the upper computer (the main hub).

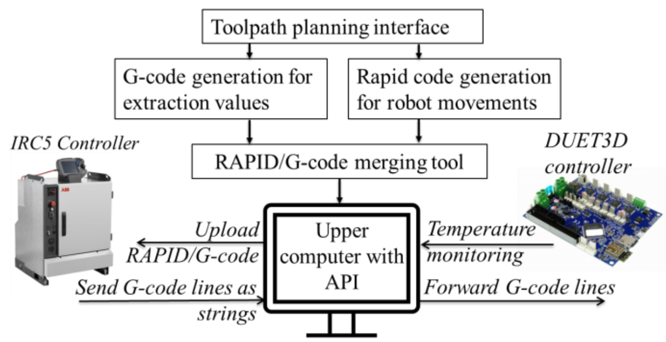

Figure 8. Communication protocol schematic.

The communication protocol described above requires solely the user's specification of the desired print curve as an input to the toolpath planning interface. All subsequent steps are automatically generated. Also providing an API on the upper computer facilitates real-time process monitoring and code line execution tracking by the user.

IV. IMPLEMENTATION

The developed hardware and software were used to additively manufacture a physical demonstrator using pre-impregnated continuous carbon fibre tow with thermoplastic matrix (Nylon 12) of Filaprem™ brand from the manufacturer Suprem (Switzerland). Specifically, the printing of a sequence of second-degree Non-Uniform Rational B-Spline (NURB) curves, each controlled by four control points, was demonstrated on both planar and non-planar (double-curved) surfaces. The developed workflow in Grasshopper was employed for this purpose, with the NURB design initially projected onto the target surface. Subsequently, the projected curve will be discretized into a series of polylines comprising non-equidistant segments determined by fibre path curvature, as explained in Section III.A.1 and shown in Figure 9.a and Figure 10.a. Following this, surface normal vectors are defined at each path point to align the extrusion head properly at the TCP perpendicular to the print bed. This process generates a series of robot targets that enable accurate execution of robotic movements. Printing parameters were integrated in the G-code. The nozzle temperature was set to 280°C and the extrusion rate was set to 300 mm/min which corresponds to TCP velocity of 5 mm/sec by the ABB robot.

In the case of planar printing, the toolpath planning required is relatively straightforward, and less extensive robotic arm maneuvering is necessary due to the uniform alignment of all surface normals in the Z-direction. The printing process, illustrated in Figure 9.b, was successfully executed on the first attempt by utilizing a resin adhesive on a glass printing bed at room temperature.

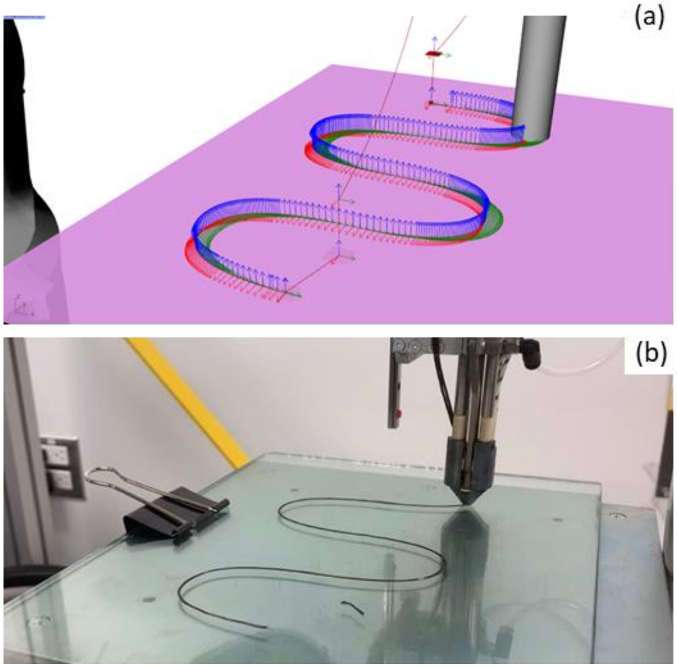

Figure 9. Demonstration of the planar print. (a) Toolpath visualization. (b) Capture from the physical printing process.

The non-planar print was carried out on a commercially on-shelf double-curved stainless-steel bowl at room temperature. The bowl was scanned using a Hexagon Absolute Arm 83 Romer V2P, 8325, 7 Axis laser scanner and imported into Rhinoceros 3D for further processing to be assigned as a work object. The bowl was mounted to a secondary robotic arm, as shown in Figure 10. The printing process is visualized in Figure 10.b. To ensure a smooth print and minimize the risk of collisions with the curved surface, additional path segments, including pre- and post-fibre path segments, were incorporated into the toolpath, as described in Section III.A.2.

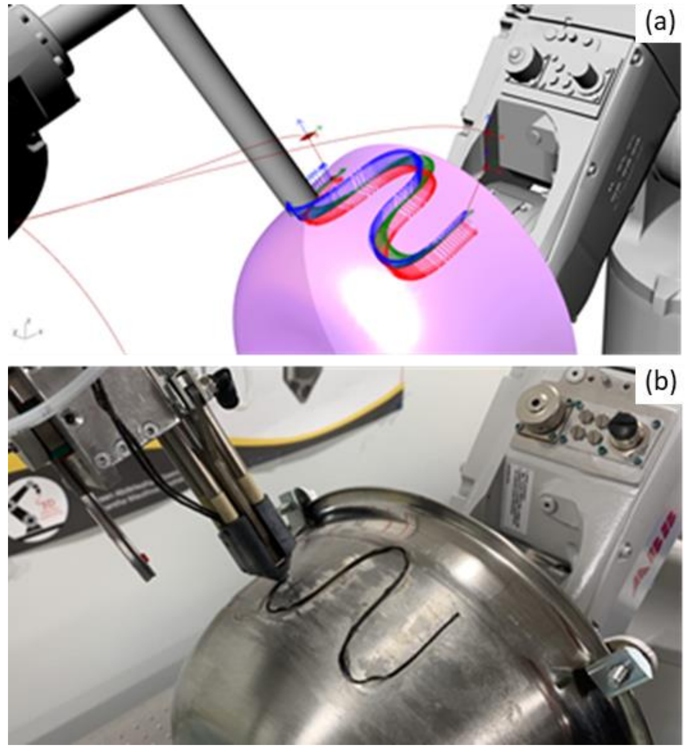

Figure 10. Demonstration of the non-planar print on a double curved surface. (a) Toolpath visualization. (b) Capture from the physical printing process.

The non-planar print encountered some challenges that affected the print feasibility and quality. First, on early print attempts, the fibre tow did not stick to the stainless-steel surface. Rapid cooling of the deposited fibre tow on the cold surface reduced the chance of initial adhesion. For this reason, glue was applied to the surface to assist the adhesion process. The glue can be observed in Figure 10.b as a white crust. Second, it was obvious that the TCP height of the extrusion head relative to the print bed was not constant. The TCP was too close to the printing bed at the start and end of the curve. This resulted in excessive spreading of the fibre tow and pilling off from the surface at highly curved segments of the tool path due to developed shear forces. Third, the TCP was separated from the surface with more than the defined deposition height at the curve middle which resulted in poor adhesion of the fibre tow.

The issues related to deposition height can be traced back to the inaccurate definition and positioning of the print bed (the stainless-steel bowl). Figure 11.a and b highlight the source of the error in yellow. First, during scanning, the edges and flange of the bowl were not accurately captured due to high surface reflection. Consequently, the distorted section of the surface was trimmed by the author, and the height of the bowl was adjusted by manual measurements. Second, the star-shaped mounting bracket used for positioning the bowl on the robot is produced from a thin aluminum plate using a water jet. The fixation holes have significant margin of tolerance, resulting in poor centering of the bowl with the sixth axis of the positioning robot. Figure 11.b illustrates the CAD model of the trimmed bowl surface and the inaccurately measured gap at fixation.

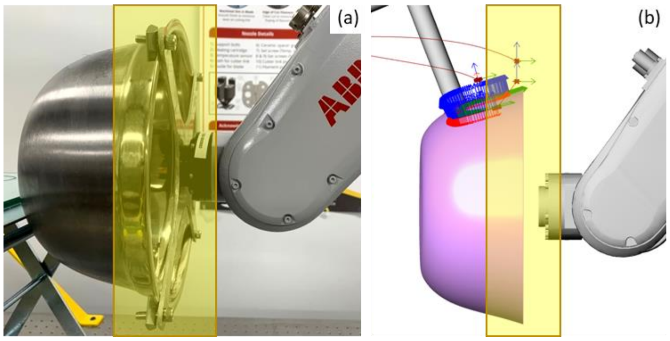

Figure 11. Side view of the printing bed (bowl with double-curved surface) mounted on a 6-axis robot. The region identified as the source of positioning error is highlighted in yellow. (a) Physical setup. (b) CAD model in Rhinoceros 3D.

V. Conclusion and Outlook

Some of the challenges of non-planar Additive Manufacturing (AM) of continuous fibre-reinforced polymer composites (cFRPCs) by means of material extrusion (MEX) have been identified in this work. Solutions have been implemented through 1) toolpath planning in 3D using 6-axis robotic arm, 2) custom design of extrusion head for continuous fibre, and 3) synchronization of the extrusion head with the robot arm for spatial and function control.

The developed toolpath workflow enabled fibre toolpath planning in 3D. It generates fibre-deposition toolpath to print any arbitrary spatial three-dimensional contours on doubly curved surfaces using a 6-axis robotic arm. Toolpath discretization into non-equidistant polylines based on the radius of the path enables smooth prints by setting the density of the path points as a function of radius of curvature. The generated polylines were used to generate G-code for extrusion length values to control the extrusion head as well as define robot frames for robot movements. Rhinoceros 3D offered a convenient interface for toolpath visualization and printing process (robot movements) simulation.

The introduced synchronization approach through CAM data management has shown success. Generating G-code and RAPID code based on the same path discretization facilitated the process of merging the G-code into the RAPID code and sending string commands to the Duet3D controller through the computer. The developed API enabled controlling the process from the upper computer (Desktop) through Transmission Control Protocol (TCP) with no need to input/output (I/O) modules, hardware connections, or external controllers like Arduino or Raspberry Pi. The developed interface is user-friendly; it requires only the definition of the fibre-path and print bed surface. The rest of the steps are generated automatically, eliminating the need to code individual lines. In addition, the printing process was controlled independently from the ABB robot manufacturer's software (RobotStudio). This reduced costs and offered flexibility in design with new custom functionalities.

The implementation of the developed toolpath planning workflow and synchronization approach has proven to be successful in the fabrication of physical demonstrators using continuous fibre on both planar and doubly curved surfaces. The planar printing process was carried out with ease, however, some challenges were faced during the non-planar printing due to issues with inconstant deposition height. These issues resulted from poor definition and positioning of the printing bed. In the future, we plan to address these challenges by manufacturing a work object (printing bed) with tight tolerance to enable more accurate positioning in the workspace relative to the nozzle tip.

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