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Toward a compact AFP head capable of performing V-shape structures:Design and Implementation

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Abstract—**This paper presents the design and implementation of a compact Automated Fiber Placement (AFP) head, addressing the limitations of conventional large AFP heads in small workspaces and complex shapes production. Traditional AFP heads, typically large and bulky, increase costs and require significant workspace, often leading to manual fiber placement that compromises product quality. Our design, developed at Concordia University, encompasses mechanical design, circuitry, and software, offering a viable solution for efficient fiber placement of a V-shape thermoset part. The experimental results show that the designed AFP head can manufacture the V-shape structure with a minimum angle of around 96 degrees and a radius of 7.5mm.**

Keywords—Automated Fiber Placement, Serial Manipulator, End Effector, AFP, Fiber Placement

I. INTRODUCTION

Composites are increasingly vital in aerospace industry due to their lightweight, high strength, and various advantages. The use of composite structures is expected to rise across various sectors of production including marine, wind energy and automotive [1]. Conventional methods for composite manufacturing, such as wet-layup or manual layup involving pre-impregnated carbon or glass fabrics, necessitate skilled technicians, are time-consuming, and an error by the technician fails the part.

An interest in automated composite manufacturing started in the 1960s [2]. Automated Fiber Placement (AFP) is a cutting-edge manufacturing technique automating fiber layer deposition onto molds for lightweight composite structures. AFPs play a crucial role, offering efficient and cost-effective manufacturing of large composite structures compared to traditional methods [3]. Although the use of AFP machines now is widely common but most of them are to manufacture shallow shells or tubes for aircraft components. In other words, many off-shelf AFP machines are not capable of producing complex shapes, closed-loop products and complex curvature tubes with Y or T shapes because of the head size and singularity issues [4, 5].

To circumvent singularity, the prevalent approach is to enhance the degrees of freedom by incorporating an extra robot. However, due to the large size of the robot heads, they are incapable of fabricating V-shaped structures with angles less than 100 and 135 degrees for thermosets and thermoplastics, respectively. As per the angle computed on a dry fiber placement machine by Dell's Anno et al, it is 120 degrees, enabling the machine to place fibers at angles greater than 120 degrees [6].

In this paper, the objective is to design a compact AFP head for Fanuc m20-iA robot capable of performing V-shape structures of thermoset with an angle as small as possible. It is important to design such an AFP head with all the process parameters needed to maintain the mechanical properties of the material and do the layup [10,11].

Thermosets are the most common AFP material used because of the ease of manufacturing process since they require a low optimal processing temperature for layup [7-8]. The temperature of the thermoset should not exceed $\approx 70\ ^\circ C$ during the fiber placement to prevent initiation of the cure reaction within the resin and they should be kept cold before layup [9].

The surface used to place the fibers on in the AFP is called a "Tool" and it is the same as the final shape aimed to be manufactured for aircraft [12], marine vehicles [13], space vehicles [14] and the one for this paper. Based on the tool and layup strategy, defining the starting points and curves throughout the surface is important to make a product with a good quality and avoid robot limitations [15].

For each AFP head, there is a need for a compaction roller to place the tow and reduce the voids between them [16]. It is well known to use segmented conformable rollers that are composed of multiple small rollers for the industrial manufacturing machines because they can move separately on a shaft [17]. There is an idea that concentrates on the tow tension to do the placement of tows [18]. When there is a high tension while placing the fibers, it is possible that this tension overcomes the adherence and makes the tows slip [19].

This paper introduces a compact, plug-and-play AFP head with thermoset material deposition capability and a user-friendly interface, aiming to meet consumer demands for manufacturing small parts with V-Shape. In contrast of the commercially available AFP head systems such as AFP-XS from (Addcomposites® company) , which are bulky and incapable of performing on the angled structure, the principal objective is to enable the designed AFP to lay up the fibers at reduced angles while maintaining design flexibility and repeatability. A Fanuc m20-iA robot is used for precise composite layer deposition.

The AFP head design incorporates essential systems and is controlled by a Fanuc m30i-B. Programmable Logical Controllers enhance digital output, and the design integrates ATI Industrial Automation's tool changer for remote tool switching. The experimental results show the design compact AFP head can lay up a V-shape thermoset part with a minimum angle around 96 degree and radius 7.5mm. The rest of the paper is organized as follows. In Section II, the mechanical design of AFP head is presented considering the constraints and components. Section III gives the design of the electrical system. In Section IV, the path planning on a V-shape structure is carried out in RoboDK Section V gives the experimental results and analysis and the concluding remark is given in Section VI.

II. Mechanical Design

A. Design objectives and constraints

To achieve the aim of designing a compact Automated Fiber Placement (AFP) head, several specific objectives and constraints must be addressed in the design process. In this paper, a Fanuc m20-iA robot is used for precise composite layer deposition. Firstly, the new AFP head must be designed to be compatible with the FANUC M-20iA robot arm, ensuring that it does not exceed the robot arm's maximum payload capacity of 20 kg (Fig.1). Additionally, the AFP head should be engineered to efficiently handle 1/4” width thermoset prepreg tows, a crucial requirement for its operational scope. A significant reduction in size is also a key goal, aiming to scale down the AFP head to approximately 20% of the size of the existing AFP head currently in use at Concordia's composites lab shown in Fig.1.

Fig. 1- Fanuc M20iA robot

Furthermore, the functionality of the AFP head on both flat and V-shaped inner surfaces is essential to broaden its application range. In terms of control and operation, the design should incorporate a seamless integration of the AFP head's subsystem controls with the Fanuc robotic arm, thus ensuring streamlined and efficient operation. The inclusion of a cooling system is vital for managing the stickiness of thermoset layers during the placement process. To enhance the AFP head's versatility, it is critical to optimize the design for effective application on the inner surfaces of V-shaped parts.

Moreover, the new design should feature a mechanism that is adept at separating non-stick membranes from the thermoset layers and collecting them efficiently. This feature would significantly improve the easiness and efficiency of the manufacturing process. Lastly, a well-designed compaction system should be incorporated into the AFP head to apply the necessary tension and force to ensure proper adhesion of the layers [16-17]. The need for pressure is necessary for the layers to be placed but it should be controlled and lowered than a limit to prevent a degradation in the mechanical properties of the fiber [17]. However, when there is a thicker laminate to be produced, the compaction pressure’s importance decreases [21]. Also, the system should be equipped with a cutting and refeeding layers mechanism for each production cycle, thereby improving the overall productivity and reliability of the AFP process [22].

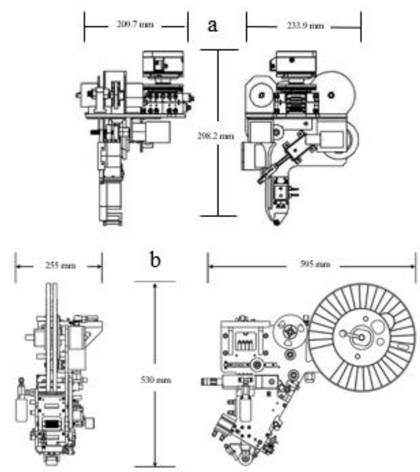


Fig. 2- Differences in the geometry and size of a common AFP head(b) and the one designed by the team (a)

B. Mechanical components

Due to the stickiness of the fibers, this fiber has a blue non sticky membrane which should be collected during the operations. Hence there is a main spool which contains the fresh thermoset tow and a collecting active spool connected to a servo motor which needs to collect the blue membrane shown in Fig.3. Regarding the tow tensioning system, it should utilize two torque adjusters to apply adequate tension to the tow prior to its deposition. Additionally, a torque adjuster is employed to gather the previously mentioned blue membrane. For the feeding system the tow is initially disconnected from the membrane at the start of each operation.

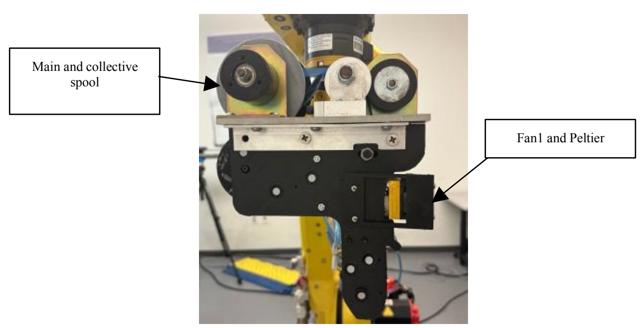


Fig. 3-Peltier, Fan, and the Feeding system

To efficiently feed the adhesive tow to the tip, an innovative approach has been adopted that involves cooling the tow using Peltier and a fan, as the fibers significantly increase their stickiness at room temperature and lose their stickiness when they are cold [23]. After the tow is advanced by a servo motor, it is laid onto a copper guide system linked to the Peltier shown in Fig.3. A pneumatic compaction system has been integrated to effectively press and guide the tow onto the surface. This system consists of a piston moving within a cylinder. A spongy roller, attached to the system, helps prevent and accommodate any misalignments during the process. The tows are fed by a motor and positioned on a guide system. Within the cutting system, a distinctive method is employed to sever the tow at the end of each course. A blade is strategically placed beneath a small aperture in the guiding system, while another blade is connected to a pneumatic system which is the same one used in the compaction system.

The project aims to design a smaller, yet efficient Automated Fiber Placement (AFP) head compared to the existing model at Concordia University, focusing on enhanced maneuverability in tight spaces without losing precision. The comparative figures shown in Fig.2 illustrate the new head is notably smaller but equally effective, offering broader application potential and ease of use. This advancement significantly boosts the AFP head's efficiency and versatility.

III. Electrical Design

A. Electrical system

The electrical system is designed considering the electrical requirements of the mechanical components. For compatibility with the system's voltage and current levels there is a need for five key electrical units. The schematic of electrical system, PLC of the Fanuc Controller, Custom-designed driver, including Arduino (Driver box), Serial manipulator electrical unit, Electrical unit for the pneumatic system and the Electrical unit for the AFP head is illustrated in Fig.4.

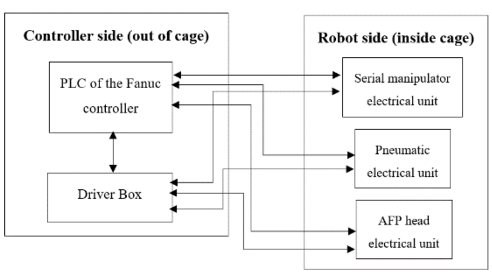


Fig. 4-Electrical controller schematic

B. Driver Box

A compact driver box for the AFP's electrical system is developed (Fig.5), comprising a 12V Voltage Supply Unit (VSU), two 5V VSUs, a stepper motor driver, an Arduino Uno, and relay switches for high current components like the Peltier and fan. The key features include an LED indicator for driver functionality, a cooling fan, and stable soldered connections using DB9, DB25, and DB15 connectors. The DB9 links the PLC to the driver, DB25 connects the driver to the robot's internals, and DB15 connects these to the AFP components.

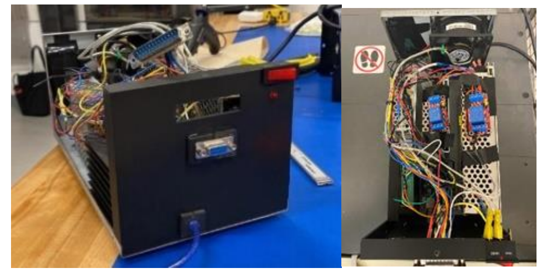


Fig. 5- Driver box top and isometric views

IV. Path Planning

For the development of the path planning algorithm, a simulation is carried out using RoboDK software. This process verifies the schematics of the AFP head to identify its geometric limitations, enabling the testing of the path planning algorithm within a narrower range of variations for V-shaped structures.

A. Geometrical based limitaion determination

The AFP's design facilitates mathematical modeling from its geometry. Notably, potential collision points include point B on the AFP's left, riskier when traversing a V-shaped part, and point C, the backing spool, vital during rotations due to the V-shape's angle. These limitations were used for primary calculations and they will be adjusted later in RoboDK simulation with detailed AFP head’s model. The 'AFP angle' is defined as the angle between the line from point A to C (right-hand limit) and from point A to B (left-hand limit on the fan fixture)[24]. Regarding the part's design (Figs 6-10), shows the part with an angle (α_p) and a radius (R_p).

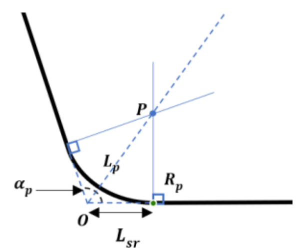


Fig. 6- Simplified schematics of the part

Figs.7-8 highlights point A (center of the roller), with points B and C representing the body and guide system and the collecting roller, respectively and ∠O is the angle of the part, L_{sr} is the starting point of the part’s curvature. The vertical and horizontal distances from points B and C from point A are L_i and H_i, respectively.

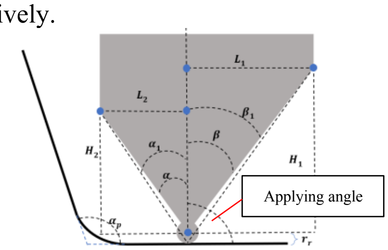


Fig. 7- Simplified schematics of the AFP based on the real design.

$$\angle O = \frac{\alpha_p}{2} \tag{1}$$

$$L_p = \frac{R_p}{\sin\left(\frac{\alpha_p}{2}\right)} \quad (2)$$

$$L_{sr} = R_p.\frac{Cos\left(\frac{\alpha_p}{2}\right)}{Sin\left(\frac{\alpha_p}{2}\right)} = Rp.Cot(\frac{\alpha_p}{2}) \quad (3)$$

The AFP head's common approach angle to the surface is 90 degrees, but to avoid collisions during fiber placement on V-shaped surfaces, rotational adjustments at certain points are necessary. To maintain the required pressure for a good fiber placement a compaction system has been used for the tow.

B. Rotations range and equiations

To determine the initial rotation for the left-side collision, point of collision which is D_r and the feasible rotation angle range (α_{r1}) were calculated (Fig.8).

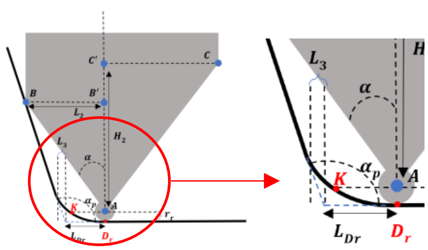


Fig. 8- Schematics of the potential collision and the first rotation point

The calculations include:

$$\tan\left(\alpha_p - \frac{\pi}{2}\right) = \frac{L_3}{r_r} \quad (4)$$

$$L_3 = r_r . \tan\left(\alpha_p - \frac{\pi}{2}\right) \quad (5)$$

$$L_{D_r} + L_3 = L_4 \quad (6)$$

where L_4 is the line between points K and A, by using the law of the sines in the triangle of KAB:

$$\frac{\sin\alpha_p}{\sqrt{(L_1^2 + \ h_1^2)}} = \frac{\sin(\frac{\pi}{2} + \alpha - \alpha_p)}{L_4} \quad (7)$$

$$\rightarrow L_4 = L_{D_r} + L_3 = \frac{\sin(\frac{\pi}{2} + \alpha - \alpha_p)}{\sin\alpha_p} . \sqrt{(L_2^2 + \ H_2^2)} \quad (8)$$

$$L_{D_r} = L_4 - L_3 = \frac{\sin(\frac{\pi}{2}+\alpha-\alpha_p)}{\sin\alpha_p} . \sqrt{(L_2^2 + \ H_2^2} \text{-} r_r . \tan\left(\alpha_p - \frac{\pi}{2}\right) \quad (9)$$

Thus, L_{D_r} represents the minimum distance from the part's corner (point O) for the first rotation, preventing AFP collision. This distance has been calculated in a way that the AFP head maintains perpendicular pressure for the longest time possible. Hence, the first rotation angle (α_{r1}) has a range:

$$\rightarrow (\alpha_p - \alpha - \frac{\pi}{2}) \leq \ \alpha_{r1} \leq (\frac{\pi}{2} - \beta) + Sin^{-1}\left(\frac{r_r}{\sqrt{(L_1^2 + \ H_1^2)}}\right) \quad (10)$$

A second rotation is necessary after the part completes its fillet section to achieve a perpendicular application angle and avoid the collision of point C. The following calculations have been conducted to pinpoint this second rotation's position (Fig.9). Note that the angle of the rotations should be chosen wisely to maintain the needed pressure for the fiber placement.

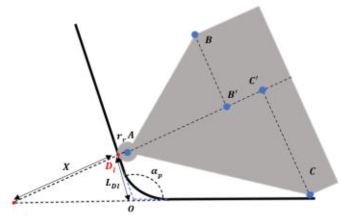


Fig. 9-Schematics of the potential collision and the second rotation point

$$X = \frac{L_1}{Cos(\pi - \alpha_p)} . Sin(\pi - \alpha_p) \quad (11)$$

$$\frac{X - H_1 - r_r}{X} = \frac{L_{dl}}{L_1} \quad (12)$$

$$\rightarrow l_{dl} = \frac{L_1 . tan(\pi - \alpha_p) - H_1 - r_r}{tan(\pi - \alpha_p)} \quad (13)$$

The second rotation angle (α_{r2}) on the left side, ensuring perpendicularity to the surface, is calculated as follows:

$$\rightarrow \alpha_{r2} = \pi - \alpha_p + \alpha_{r1} \quad (14)$$

C. Rotations and positions

Fig.10 illustrates the robot's path, starting from Point S and progressing to the first rotation at Point D_r. From there, it moves to Point P_1, followed by a circular path to P_2, using P_m as the pivot then advances to Point D_l for a subsequent clockwise rotation. After, it follows a linear path to the final point, Point E.

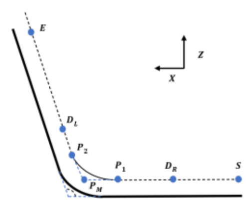


Fig. 10- Rotation positions

$$\text{Position of Point } S = \begin{bmatrix} 0 \\ 0 \\ r_r \end{bmatrix} \quad (15)$$

$$\text{Position of Point } D_r = \begin{bmatrix} l_p - l_{Dr} \\ 0 \\ r_r \end{bmatrix} \quad (16)$$

First rotation matrix with the rotation of α_{r1} degrees=

$$R_{r1} = \begin{bmatrix} \cos\alpha_{r1} & 0 & \sin\alpha_{r1} \\ 0 & 1 & 0 \\ -\sin\alpha_{r1} & 0 & \cos\alpha_{r1} \end{bmatrix} \quad (18)$$

$$\text{Position of Point } P_1 = \begin{bmatrix} l_p - l_{sr} \\ 0 \\ r_r \sin(90 - \alpha_r) \end{bmatrix} \quad (19)$$

Position of Point P_2 =

$$\begin{bmatrix} l_p + (l_{sr}\cos(180 - \alpha_p)) \\ 0 \\ (l_{sr}\sin(180 - \alpha_p)) + r_r \sin(\alpha_p - 90 - \alpha_r) \end{bmatrix} \quad (20)$$

Second rotation matrix with the rotation of α_{r2}=

$$R_{r2} = \begin{bmatrix} \cos\alpha_{r2} & 0 & \sin\alpha_{r2} \\ 0 & 1 & 0 \\ -\sin\alpha_{r2} & 0 & \cos\alpha_{r2} \end{bmatrix} \quad (21)$$

Position of Point E =

$$\begin{bmatrix} l_p + (l_p\cos(180 - \alpha_p)) - r_r \cos(\alpha_p - 90 - \alpha_r + \alpha_l) \\ 0 \\ (l_p\sin(180 - \alpha_p)) + r_r \sin(\alpha_p - 90 - \alpha_r + \alpha_l) \end{bmatrix} \quad (22)$$

D. Path planning

Path planning is crucial as it combines the robot's trajectory with the tool's surface geometry to dictate fiber layer orientations, and for the composite's integrity. Additionally, the robot's configuration, such as arm length and articulation, significantly impacts the placement's feasibility and precision. The challenges primarily involve managing the number of fiber tows and their arrangement, including calculating gaps and overlaps crucial for the composite's mechanical properties. Proper alignment of the head with the path's tangent vector ensures fibers are correctly oriented. Maintaining the correct length between tows within the maximum tow width is crucial for accurate component forming. It's important to align the AFP head with the structure surface's normal vector. This ensures the head stays perpendicular to the surface, which is essential for uniform fiber deposition, necessary pressure application, and defect avoidance. Offline path planning programs like RoboDK are essential for analyzing and validating robot paths and for pre-testing simulations to identify potential issues, significantly reducing errors and enhancing the efficiency of implementation.

E. RoboDK and the algorithms for the rotation

The proposed simulation, using RoboDK, involves laying fiber prepregs on a V-shaped CAD file, focusing on collision prevention. The AFP head, shaped by CAD geometry, allows for a minimum achievable angle of about 95.2 degrees with a 7.5 mm radius, equal to the roller's radius. The simulation focuses on collision avoidance and facilitates multi-layer fiber placement. It ensures each layer is strategically offset to accommodate fiber width and desired gaps. Fig.11 shows the test using a minimum radius of 10 mm, and the smallest practical simulation angle is rounded up to 81 degrees also it shows the first rotation to avoid collision. To verify these calculations and ascertain the smallest feasible angle, 3D models of V-shaped parts are created using SolidWorks and Catia software, then imported into RoboDK for path planning, applying previously developed algorithms in this simulation environment.

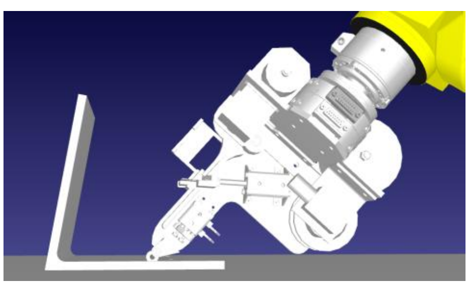


Fig. 11- AFP and Part in the simulation environment (RoboDK)

V. EXPERIMENTAL RESULTS AND ANALYSIS

A. Experimental Setup

The experimental setup of the AFP system consists of one 6 DOF serial manipulator, a small size fiber placement head, the Driver box, the robot's controller, and the tool (Fig.12).

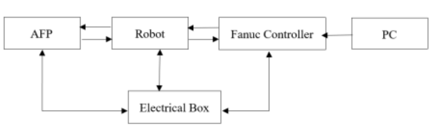


Fig. 12- Hard drive structure

This study focused on creating a small-scale AFP for fiber placement on V-shaped structures and then the minimum angle for this structure was calculated as 95.2 degrees. Key angle and radius values, determined earlier, guided the 3D printing of a test object. This object was then reinforced with aluminum plates and equipped with a specially designed back support for the 96-degree part with 7.5 mm radius in the corner, as shown in Fig.13.

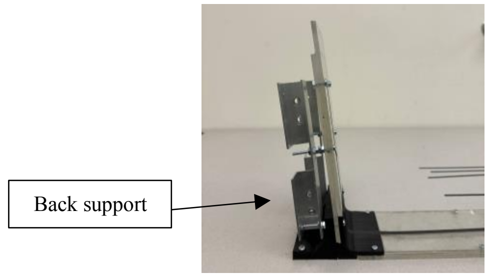
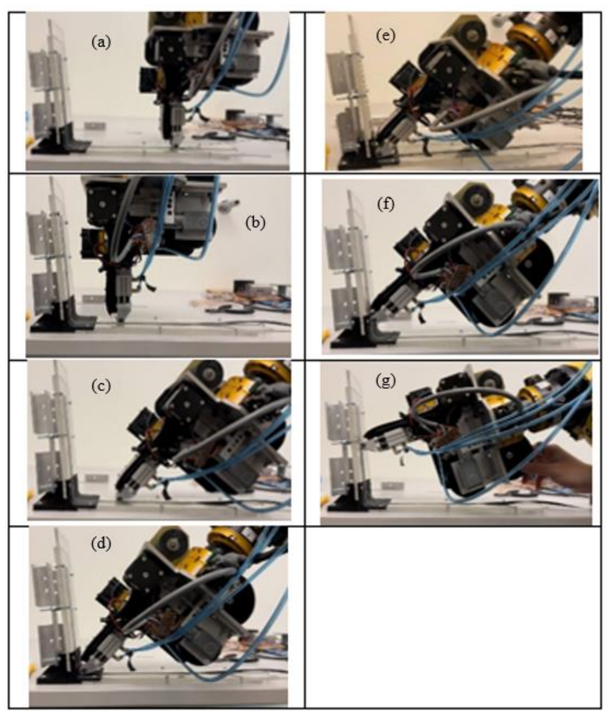


Fig. 13- Test setup for 96 degrees test part

B. Test Steps

The path planning algorithm is integrated into the robot via a Teach pendant, enabling precise fiber placement by guiding the AFP robot's rotations. The algorithm's effectiveness is confirmed as the robot successfully placed fiber on the test object without any collisions. In table 1 it is shown that the robot starts the path(a) reaches the first rotation point(b)rotates(c) and continues the path (d) until it reaches the curvature of the part(e) and starts the circular movement till it's finished(f) again the path is linear and continues till it reaches the second rotation point(g) when the final rotation is done it continues till the end of the part. It is also important to mention that there is a specific point with a specific distance from the end of the path that the cutting system should cut the fiber.

Table 1- THE EXPERIMENTAL TEST STEPS



C. *Results and Analysis*

To determine acceptable values for the parameters, each is assessed individually, fixing one while varying the other. For simplicity and to avoid redundant data, only the critical values within critical ranges for both parameters are presented. Below 73 degrees, the AFP will invariably collide with the part, conversely, there will be no collision above 135 degrees, irrespective of changes to the other parameter. After conducting the test on the simulation environment and in the real time operation, it has been found that the minimum angle and radius that the AFP head can perform is 96 degrees and 7.5mm accordingly.

Table 2-Final results by changing all the parameters.

Collisions (✓ or ×)	**Angle (Degrees)**								
Radius (mm)	*74*	*75*	*76*	*77*	*78*	*79*	*80*	*81*	*82*
10	✓	✓	✓	✓	✓	✓	×	×	×
20	✓	✓	✓	✓	✓	✓	×	×	×
30	✓	✓	✓	✓	✓	✓	×	×	×
40	✓	✓	✓	✓	✓	×	×	×	×
50	✓	✓	✓	✓	✓	×	×	×	×
60	✓	✓	✓	✓	✓	×	×	×	×

To make these values smaller it is important to know that the AFP angle is a critical factor in AFP operations, with the goal being to minimize it for optimal fiber placement.

VI. Conclusion

In this paper, a compact AFP head capable of performing V-shape thermoset structures is designed and implemented. Both mechanical and electrical systems are designed considering the constraints and manufacturing requirements. A path planning for a V-shape structure is carried out in RoboDK simulation environment to find the value of smallest feasible angle for implementation. The experimental results demonstrate that designed AFP head can manufacture the V-shape structure with a minimum angle of 96 degree and radius 7.5mm. Future work includes collaborating with other robots to increase the flexibility and performance of fiber placement and singularity avoidance. This research is significant in advancing compact AFP technology for V-shaped structures, demonstrating a promising direction for future AFP innovations and material technology applications

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