

**Designing and implementing a small-size Automated Fiber
Placement (AFP) head capable of depositing thermoset
layers on V-shape structures**

Alireza Saboukhi

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By: **Alireza Saboukhi**

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and submitted in partial fulfillment of the requirements for the degree of

Master of Applied Science (Mechanical Engineering)

complies with the regulations of this University and meets the accepted standards with respect to originality and quality.

Signed by the Final Examining Committee:

Dr. Brandon Gordon Chair

Dr. Brandon Gordon Examiner

Dr. Farjad Shadmehri Examiner

Dr. Wen-Fang Xie Supervisor

Dr. Suong Van Hoa Co- Supervisor

Approved by

Martin D.Pugh, Chair

Department of Mechanical and Industrial Engineering

2023

Mourad Debbabi, Dean

Faculty of Engineering and Computer Science

ABSTRACT

Designing and implementing a small-size Automated Fiber Placement (AFP) head capable of depositing thermoset layers on V-shape structures

Alireza Saboukhi

Automated fiber placement (AFP) is an advanced manufacturing technology used to manufacture light weight composite structures by depositing the fiber layers using robotic manipulators and is notably applied to aerospace components manufacturing. However, the commercially available AFP machines are designed to manufacturing simple structures like shallow shells or tubes and they are large and bulky therefore they are incapable of handling some applications with more complex shapes and in small workspaces.

A small-size AFP head is proposed to manufacture complex composite components and fulfill other objectives of the project such as having the ability of depositing layer on the flat surface. The AFP head is attached as a tool to the end effector of a FANUC M-20iA 6 degree-of-freedom (DOF) serial robot. It utilizes a thermoset tow of ¼ inch width, and is designed to be small size and optimum as possible to ensure optimal maneuverability in order to place the Fiber on the inner surface of V-shaped structures. This system consists of the aforementioned robot, the AFP head, the controller of the Robot arm Fanuc system R30i-B and a computer which the operator could use for generating the path using the proposed algorithm. The solutions required mechanical system design and implementation, electrical circuit design and implementation, and path planning programming. Two offline programming path planning algorithms using RoboDK post processor are developed for depositing the layers on the flat surface and on the inner surface of V-shaped structures. A software package has been developed to generate the full code and send it to the controller of the robot. Hence the operator is able to run the code directly with the Teach pendant (TP) of the robot.

The simulation has been conducted in the RoboDK software package based on the determined minimal angle and the limitations which have been calculated by deriving the mathematical model from the geometry of the AFP and the test parts. Experimental results also demonstrate the successful path planning and fiber placement machining procedure.

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List of Abbreviation

AC	Alternating Current
AFP	Automated Fiber Placement
API	Application Programming Interface
CNC	Computer Numerical Control
DOF	Degree of Freedom
DC	Direct Current
FEA	Finite Element Analysis
GUI	Graphic User Interface
Kg	Kilogram
MPa	Mega pascal
mm	Millimeter
M/S	Meter/Second
M/S ²	Meter per second squared
N.m	Newton meter
PLC	Programmable logic controllers
RPM	Revolution per Minute
TP	Teach Pendant
VSU	Voltage Supply Unit

Chapter 1

1 Introduction

1.1 Overview

Composite materials have found extensive usage across various industries, including aerospace, automotive, wind power, civil infrastructure, medical equipment, and more [1]. In general, composite materials exhibit several advantages over traditional structural materials like steel, aluminum, or titanium alloys [2]. These advantages include being lightweight, having superior chemical and corrosion resistance, better impact resistance, excellent mechanical properties, increased design flexibility, and attractive strength-to-weight and stiffness-to-weight ratios. For instance, in the aerospace industry, composites are used to make lightweight aircraft parts that can withstand the stresses of flight. Roughly 50% of the total weight of the Boeing 787 is composed of composites which is the reason that despite of the capacity of 200-250 passengers it uses 15-20% less fuel than other airplanes [3]. The use of composite structures is expected to rise across various sectors of production, including aerospace, automotive, marine, and wind energy. In light of this, Original Equipment Manufacturers (OEMs) and material suppliers are continually seeking new materials and techniques that can accommodate the increased production volumes while simultaneously reducing costs and maintaining the quality and performance of prepreg systems. Several such processes have been developed, including Resin Transfer Molding

(RTM), Out-of-Autoclave (OOA) materials, Vacuum Assisted Resin Transfer Molding (VARTM), and Controlled Atmospheric Pressure Resin Infusion (CAPRI)[4].

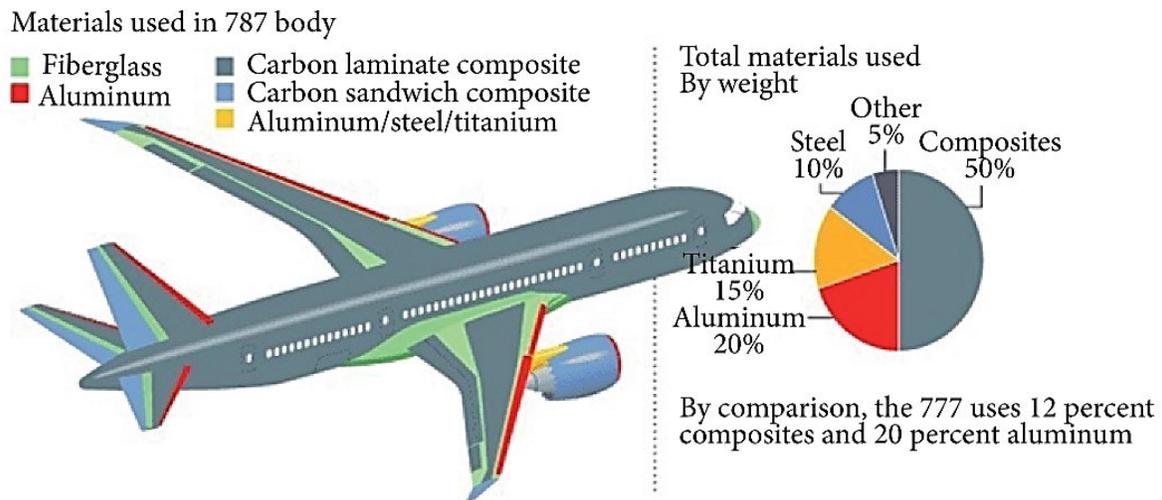


Figure 1-1 Use of advanced composite materials in Boeing 787 Dreamliner [5], [6]

The traditional approaches to composite manufacturing, such as wet-layup or hand layup of pre-impregnated (prepreg) carbon or glass fabrics, require skilled technicians and involve time-consuming work. This limits the potential for significant advancements in the field. However, automated composite manufacturing techniques like Automated Fiber Placement (AFP) or Automated Tape Laying (ATP) machines have emerged as production methods that can address many industry requirements that were previously impossible with traditional methods. Furthermore, standardized tape sizing formats for conventional prepreg systems are now available, which enable automation of the process. In numerous industries, automation of production is vital to meet rising demands, enhance quality, ensure repeatability, and reduce costs. While composite manufacturing remains relatively labor-intensive, efforts are being made to increase automation levels. Research and interest in automated composite manufacturing date back to the 1960s, with the advent of automated filament winding systems, and AFP/ATL systems in the 1970s [7]. Figure 1-2 provides an overview of the volume of archived publications on automated composite manufacturing over the years.

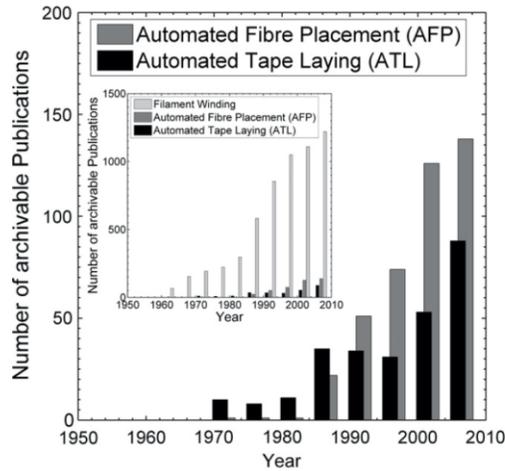


Figure 1-2 Automated Manufacturing using AFP and ATL comparison from the 1970s [7]

The integration of robotic technology and expertise in composite materials has given rise to a novel manufacturing technique called Automated Fiber Placement (AFP). An AFP machine comprises a robotic arm and a manufacturing head, with the arm positioning the fiber placement head in specific locations and moving it around the space, while the manufacturing head applies pressure to the tapes laid on the part. AFP machines are capable of producing both thermoset and thermoplastic composites. In the case of thermoset manufacturing, the machine deposits the material on the mandrel, and the part is then cured in an autoclave for final production. However, for thermoplastic manufacturing, the AFP machine also features a heat source that elevates the tape's temperature just before it is deposited. A photo of an AFP machine with a thermoplastic head is shown in Figure 1-3 [8].

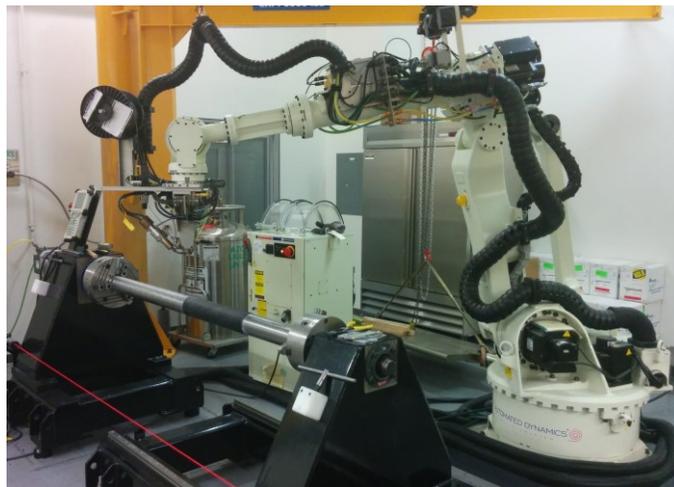


Figure 1-3 A picture of the AFP machine at Concordia University [8]

The aforementioned AFP machine is located at Concordia University CONCOM (Concordia Center for composites) laboratory which is a ZX130L Kawasaki 6-axis articulated robot arm, which can withstand a payload of 125 kg. Two interchangeable heads manufactured by Automated Dynamics can be attached to the robot arm: a thermoplastic (TP) fiber placement head and an independent tow control (ITC) thermoset (TS) head [9].

1.2 Problems and Solutions

Although AFP machines have been successfully used in industry manufacturing processes, most current designs are for manufacturing shallow shells or tubes for airframe components [10], such as the machine at Concordia University shown in Figure 1.3[8]. Also, other examples of AFP systems utilized in today's automated composite manufacturing industry are depicted in Figure 1-4. They are not capable of producing more complex shapes, such as a bicycle frame with a closed loop, a fan blade with complex curvatures, tubes with T or Y shapes[10], or tubes with flanges in circular shapes, like exhaust ducts in jet engines depicted in Figure 1-5.

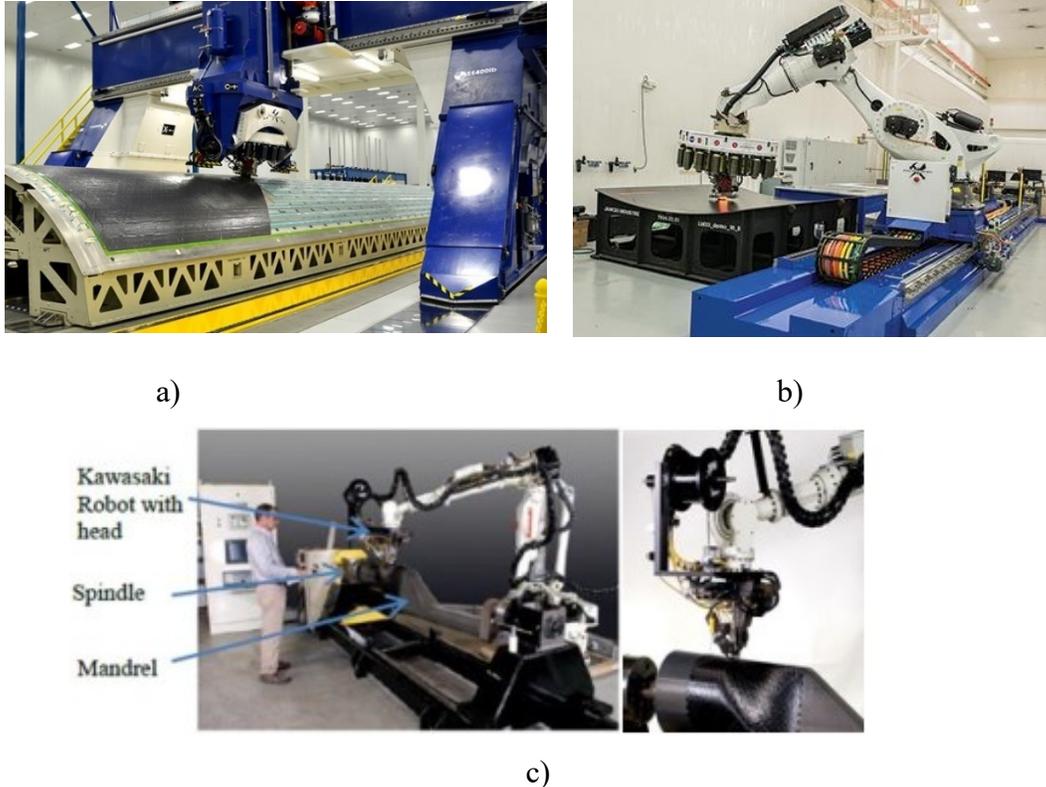


Figure 1-4 A few industrial AFP machines: a) gantry style AFP machine [10], b) Robotic arm AFP with removable head on rails [11], c) Automated Dynamics AFP head [10]



Figure 1-5 Structures and frames with Complex Shapes[10]

To expand the manufacturing capabilities of AFP machines in a simple and low-cost way, increasing the number of degrees of freedom (DOF) of the robotic system is necessary. As it has been mentioned before, the Concordia composites lab has an AFP machine, but it is designed for aerospace components and is too bulky for certain projects that involve small structures and tight spaces. Upon conducting measurements of the angle between the right side and left side lines of the AFP for both the Thermoset (Figure 1-7) and Thermoplastic head (Figure 1-6), it became evident that this angle is equal to 100 degrees and 135 degrees, respectively, which unable the AFP heads to layup in V-shape or L-shape structures with less degrees than aforementioned degrees.



Figure 1-6 Thermoplastic AFP head at Concordia University

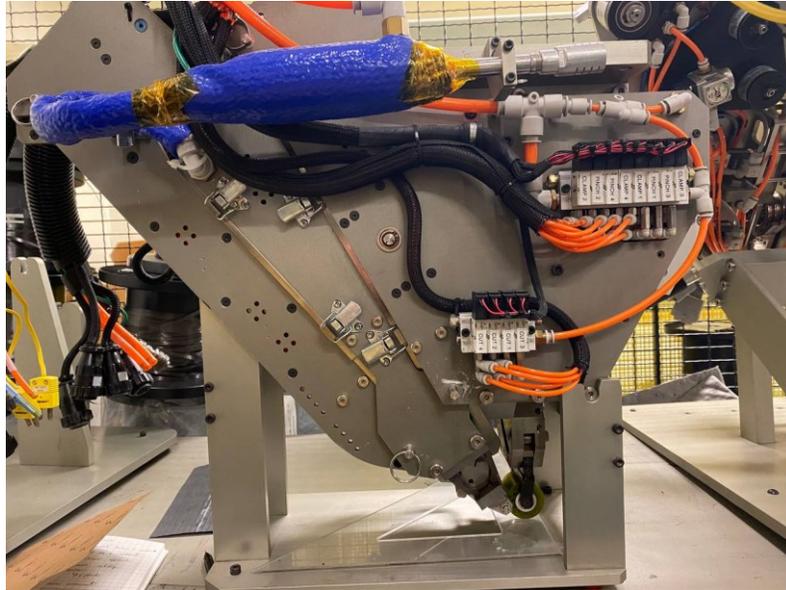


Figure 1-7 Thermoset AFP head at Concordia University

It is worth mentioning that according to Figure 1-8 the angle that has been calculated on the automated dry fiber placement machine's schematic is equal to 120 degrees in the study conducted by Dell'Anno et al.[12].

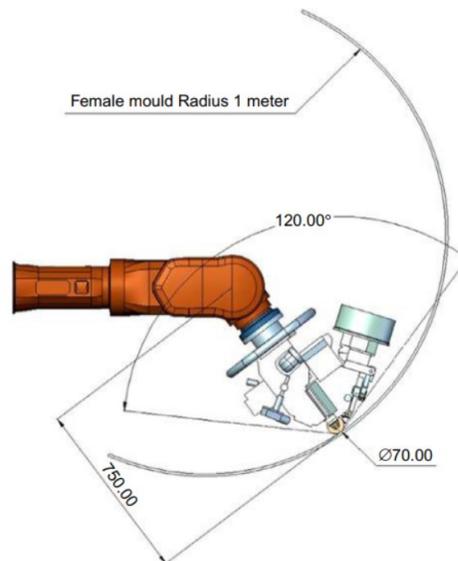


Figure 1-8 Schematic of ADFP (Automated Dry Fiber Placement) deposition head[12]

Therefore, a pressing need exists for a small Fiber placement robot end effector that can operate in more constrained locations and produce structures with finer detail. This would reduce

the spatial limitations of the current technology and enable the production of more complex shapes. To this end, this project focused on developing a small-size fiber placement (AFP) head capable of depositing fibers on the inner surface of a V-shaped structure.

It is worth mentioning that, the fiber placement head should be designed to fit on a FANUC M-20iA robot arm and uses a ¼" width thermoset tow which is shown in Figure 1-9.



Figure 1-9 ¼" width thermoset tow

Additionally, the objective requires that the head be as small as possible. The AFP head must perform three active operations: tow feeding and tensioning, compaction of the tow to ensure strong adhesion to the workpiece, and cutting of the tow at the end of each placement run. The primary goal of the design is to enable composite deposition on flat surfaces as well as more complex surfaces, such as concave half-circles, and the inner corners of V-shaped and Y-shaped structures. Figure 1-10 shows the Fanuc m20-iA robot located at Concordia University's Robotics Lab.



Figure 1-10 Fanuc M20-iA Serial Manipulator

1.3 Scope and Objectives

The purposes of this project are to redesign the AFP system developed by undergraduate students in order to have a functional and compact AFP head. This AFP head should be installed on a 6 DOF serial robot as its tool in order to manufacture composite material components with more complicated structures and tight corners. In order to fulfill those objectives, a small size AFP head is proposed which includes all of the required mechanical and electrical systems.

The control of the robot should be based on path planning which is subject to the constraints of the part and robot. The objective for the AFP is to deposit the composite prepreg layers on the inner surface of a V-shape part, with the V angle as small as possible. Hence, a limitation of inner angle of V-shape structure for collision avoidance should be considered in the redesign phase.

In order to have an automated fiber placement machining, a path planning algorithm is required. There are two main path planning methods such as offline and online path planning. However, in this thesis project, due to the limitation of sensors and software in the project, the offline programming method is adopted for path planning. This method should consider the parameters such as radius and angle for the V-shape part fiber placement and speed, gaps, overlaps, length, and width for fiber placement of a flat surface.

Due to the limitation of resources and lack of time for building the AFP head more than one time, a simulation is required for the process before implementation in the experimental tests. Hence, a simulation is proposed for laying up the fiber prepreps on a V-shape CAD file to avoid the collision using RoboDK simulation and path planning feature. Due to the potential collision, the roller of the AFP head can not be perpendicular to the surface of the part all the time. Hence, some specific rotations are needed based on the features and angles of the AFP head and the part. On the other hand, the flat surface fiber placement does not require any simulation because the roller is always perpendicular to the surface of the part.

To meet the challenge, the geometrical models of AFP head and V-shape structure are built, and values should be measured and have to be implemented in the simulation.

It should be noted that the aforementioned rotations are only varying the poses of the roller and the position will not change in during of the rotations.

After verifying the fiber placement procedure and finding the smallest possible angle and radius in the simulation, these values will be used in the algorithms for the path planning for the robot in experimental tests. Some software implementing the developed algorithms with GUI should be developed for each of the fiber placement methods, and the final goal is to run a successful experiment for reaching the smallest possible angle and radius.

1.4 Thesis organization

This thesis consists of 6 chapters. The outline of the thesis is given as follows.

- Chapter 1 summarizes the overview of composite material and the AFP machine. The main problem of the current machine and solutions are introduced. The scope and objectives of the project are subsequently given.
- Chapter 2 presents the literature reviews on the current AFP machines, path planning methods, simulation software, and the usage of serial manipulators in AFP machining.
- Chapter 3 presents the manufacturing and implantation processes of building the desired AFP head. In this chapter, the design constraints, and designs of both mechanical and electrical systems are presented.
- Chapter 4 presents the geometrical modeling of AFP head and V-shape structure. The software and algorithms implementation steps are demonstrated. The simulation is done using a simulation environment software package (RoboDK).
- Chapter 5 introduces the experimental setup of the AFP systems which consists of one 6 DOF serial robot, the proposed fiber placement head, the Driver box, the controller of the serial robot, and two testing parts for each test. The hardware setup of the AFP system is illustrated. The tests demonstrate the process of fiber placement on a flat surface and the inner surface of various V-shaped parts. These processes have been carried out through manual programming and also offline path planning programming.
- Chapter 6 summarizes the conclusions and contributions of the project. Further studies are recommended.

Chapter 2

2 Literature review:

A literature survey on the relevant studies regarding the current AFP machines and path planning and usage of serial manipulators for AFP machines is conducted in this chapter.

2.1 AFP machines

Initially, composite manufacturing processes relied on manual lay-up, followed by consolidation and curing in an autoclave. Although the hand lay-up method provided better compatibility than other methods for certain complex parts, it was time-consuming and relied heavily on the experience of technicians, which resulted in higher manufacturing costs and variable production quality [13], [14]. Hence, there have been numerous research studies aimed at developing automated composite manufacturing processes, while also enhancing the associated devices and technologies to achieve greater flexibility, multifunctionality, and efficiency. Two primary automation technologies that are currently utilized for manufacturing large composite components are automated tape laying (ATL) and automated fiber placement (AFP). Through the use of these automated processes, labor-intensive activities are greatly reduced, and manufacturing efficiency is improved to a significant degree[15].

By taking advantage of the ability to individually control each fiber, AFP technology can produce a fiber band of varying widths, which enables the creation of more intricate surfaces with greater precision and less material waste when compared to ATL processes[14].

Since 1997, researchers have made systematic advancements in composite manufacturing technologies, leading to innovative explorations and comprehensive discussions of detailed findings and perspectives. For instance, Grant et al.[15] offered an overall assessment of processing techniques such as ATL, AFP, and winding machines, and identified a growing inclination towards cost-effective automation in composite manufacturing. The study conducted by Dirk et al.[7] centered around the advancement of prepreg layup through the use of AFP and ATL. They also provided a comparison of the constraints and limitations of these machines. Despite its crucial role in the quality of composite forming, there has been a relative lack of focus on reviewing the mechanisms, mechanical structures, and research improvements related to AFP systems. Hence, an overview has been done by Zhang et al. [14] to present the mechanisms of the automated composite manufacturing methods, advantages and disadvantages, and the critical process parameter control of AFP, including minimal fiber length, tension, and compaction force.

2.1.1 History and development of AFP

AFP, ATL, filament winding (FW), and resin transfer molding are common techniques used for fabricating fibers. The FW machine was initially developed in the 1940s and was successfully utilized for rocket motor cases. Later on, in the late 1960s, ATL was introduced for various military programs, such as the manufacturing of missile shells[15].

In the late 1970s, following the growth of the aircraft industry and advancements in composite materials, the concept of the AFP process was introduced to address the limitations of the FW and ATL processes. Alongside this, developments in fiber reinforcement manufacturing facilitated the emergence of AFP system manufacturers, which led to significant economic and mechanical property benefits.

American manufacturing companies, Hercules Aerospace (ATK) and Cincinnati Machine were among the first to develop their AFP systems in-house during the early 1980s. Since then, various manufacturers and institutions, including Automated Dynamic, MAG Cincinnati, Ingersoll Machine, Electroimpact Inc., ATK, and Accudyne from the USA, MTorres from Spain, Mikrosam

from Macedonia, and Coriolis from France, have been extensively involved in the development of AFP systems [14]. Automated Dynamic Cooperation and Coriolis utilize industrial robots to provide AFP systems with up to eight-bundle fibers for research and design studies conducted by institutions and universities. Cincinnati, Ingersoll, Accudyne, ATK, MTorres, and Mikrosam mainly use CNC machine tool technology to meet industrial demands, such as manufacturing wing stringers, fuselage sections, panels, and pressure bulkheads for aircraft programs and automation. Electropact, MTorres, Automated Dynamics, and Coriolis develop several types of systems based on a modular design approach with high integration levels. In comparison to automated tape laying (ATL) systems, AFP systems use 1, 2, 4, 12, 16, 24, or 32 individual slit prepreg fibers, usually with a width of 0.125–0.500 in, to manufacture more complex curved surfaces and small structures, which can also be customized according to customer needs [16].

In terms of flexibility and affordability, although using industrial robots for AFP systems can provide solutions for modular equipment as compared to gantry units, the initial investment for an AFP manufacturing process remains high. To reduce the cost of production, another approach is to improve productivity and functionality once the requirements are met. For instance, Izco et al. [17] designed an AFP machine with the ability to clamp, cut and restart (CCR) individual fiber tows at high speed, resulting in a significant increase in productivity of more than 45 kg/h. This machine is currently available in the market. Furthermore, a team of researchers from Italy has designed a novel tape placement technique that involves two compacting rollers to enable alternative deposition movement. This system is capable of continuously laying up structures with variable thicknesses [18]. Addcomposites Company [19] began developing AFP tool heads in 2017, aiming to explore the convergence of AFP and 3D printing or the integration of multiple processes into a single automated tool to reduce costs. However, to the best of our knowledge, there has been no research done on implementing this approach for the design of AFP systems' mechanisms.

An AFP system usually consists of three main components: an AFP mechanism, computer-aided manufacturing (CAM) software, and a moving platform. The moving platform is typically an industrial robot [20], although it can also be a gantry, column configuration machine, or customized design [21]. The CAM software is used for trajectory planning and fiber path

generation, while the AFP mechanism is responsible for independent fiber delivery and control of process parameters to achieve precise fiber layup.

Thus, the AFP manufacturing industry is mainly concerned with mechanical design, process parameter control, and trajectory planning technologies [22], as these are essential for coordinating the functional mechanisms to supply independent fibers with individual feed speed and tension control to form composite parts. However, the functional mechanisms in AFP systems are complex, involving multiple degrees of freedom, multiple actuators control, and complex coupling constraints. Therefore, a clear understanding of these modules and their interactions is necessary to describe an AFP process effectively.

2.1.2 Automated fiber placement mechanisms design

This section consists of the essential mechanisms of the whole AFP which includes the main structure of the AFP mechanism, creel assemblies, CCR mechanisms, compaction mechanisms, and heating system.

2.1.2.1 The main structure of AFP assemblies

The AFP mechanism is a crucial component in the production of composite parts using fiber placement systems. It is responsible for delivering composite tows with low tension and sufficient compaction pressure at an appropriate temperature while in contact with the mould surface. Goldsworthy [23] proposed a composite-tow placement mechanism in 1974, which included a path length compensator to address the limitations of the tape placement head, such as tension maintenance and laying of tows on curved surfaces. In 1986, Pugh [24] introduced an advanced variable strand dispensing machine with a clamping and cutting mechanism and a pre-compaction roller, which was still in the early stages of development for AFP. These mechanisms and processes have been adopted by manufacturers such as MAG, Ingersoll, and ENGEL, as well as many other industrial fiber placement systems. Furthermore, the single-fiber tow transmission which has been done by Vaniglia [25] has been shown in the following figure, which serves as the basis for these mechanisms.

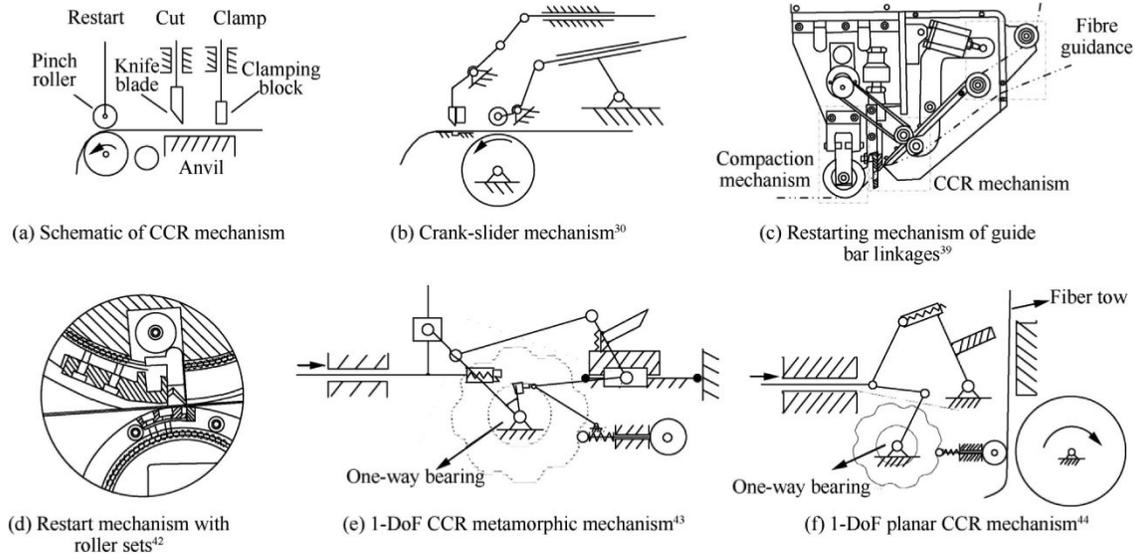


Figure 2-1 Typical CCR mechanisms[14]

2.1.2.2 Creel assemblies

The AFP process requires creel assemblies to hold the composite materials, which are classified into three types: thermoset fibers, thermoplastic fibers, and unsaturated dry fibers. Thermoset fibers have a finite shelf life and require specific storage conditions, while thermoplastic fibers do not need cooling. To address these issues, creel assemblies are mounted separately on a cradle, and a redirect mechanism is provided between the creel assembly and the AFP mechanism for more than 16 fiber tows [26]. This modular approach allows for the rapid interchange of creel assemblies, resulting in higher lay-up speed and precision due to the weight reduction of the AFP head. However, it also involves complex maintenance and fiber guidance. For instance, the Coriolis C1 and C2 and the Ingersoll Lynx series. It is crucial to maintain a sufficient distance between the coils and the compaction roller to prevent any false twists resulting from the winding of the coils. This is the same for the Concordia's Lab thermoset AFP head which is one of the main reasons for being incapable of doing V-shape and small structures.

2.1.2.3 CCR Mechanism

The focus of many approaches so far has been on the fundamental assembly of the AFP mechanism, specifically the CCR mechanism, which enables individual control for each fiber strip,

largely based on lessons learned from ATL systems. The CCR mechanism operates in a strict sequence, as depicted in the figure, with a clamping block fixed with a blade and driven by the same actuator to ensure movement sequence and reliability. Vaniglia [25] introduced a pneumatic driver that connects a crank bar with a knife and a block, which is activated to shear a tow and pinch the cut end of a fiber tow. Izco et al.[17] proposed the use of a rotary system as a critical technology to CCR, employing a rotary actuator to increase productivity. A piston-cylinder or an ultrasonic transducer assembly with a blade is used to directly cut fiber tows. To improve the quality of the cut and the layup precision, the distance between the knife blade and the compaction roller, also known as the "minimal fiber length," should be minimized.

To improve the efficiency of restarting a tow and reduce lag times, Tingley[27] proposed using an additional roller apparatus to match the speed of the compaction roller. Oldani and Jarvi [28] proposed a method with a time-based tool path to perform high-speed cutting or adding of tows with considering the latency value. Based on the relationship between cutting, clamping, and restarting, some researchers have designed mechanisms with a reduced number of motors to perform these functions, as shown in Figure 2-1.

Vaniglia [29] presented in another patent a roller set that includes gear pairs with two cutters and clamping zones, as shown in Figure 2-1(d), which can press a fiber to a restart pinch roll assembly for an AFP machine. Moreover, various new mechanical theories have been utilized in CCR mechanisms.

The mode of actuation determines the design of CCR mechanisms in theory. Linkage mechanisms and direct drive models are commonly used for linear actuators, such as pneumatic cylinders, due to their high reliability. However, they require complex drives, increase the overall volume and weight of the AFP system, and incur higher maintenance costs. On the other hand, a single actuator can be used to accomplish the movements of CCR, improving actuator efficiency but decreasing system reliability in case of mechanical failure. Therefore, extensive mechanism design concepts and structural optimization are necessary to establish a paradigm for combining modules freely. To achieve excellent performance for these functions, further research is required, involving modern mechanism theories and configuration synthesis[14].

2.1.2.4 Compaction Mechanisms

The compaction setup is crucial in the composite consolidation process, as it affects the porosity content both within and between layers. To address this, early development such as [25] focused on designing pneumatic cylinders and compact segments within a flexible roller, as seen in previous studies. For instance, some AFP mechanisms [30] incorporated a compaction mechanism with a flexible outer layer to provide a linear stroke length, allowing for the production of stiffening structures with complex curved parts, as shown in Fig 2-2.

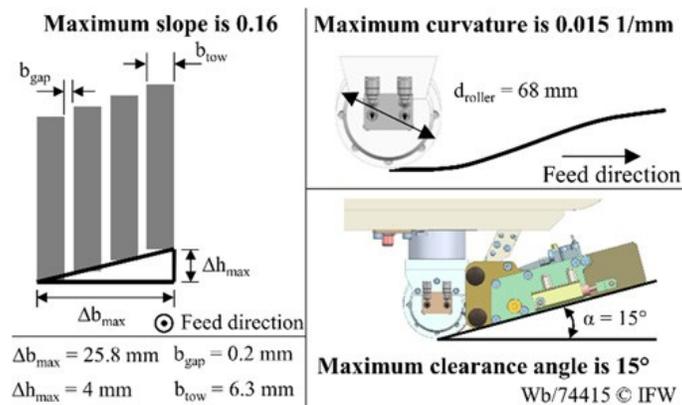


Figure 2-2 Flexible outer layer for roller [30]

An adaptive compaction roller was developed by Steeg et al.[31] for thermoplastic fiber placement, which is capable of compensating for minor angle deviations that may exist between the compaction roller and the surface of the mould. Multiple roller mechanisms have been widely studied as a means of consolidating thermoplastic composites, offering the benefits of improved intimate contact and suitability for out-of-autoclave processes. For instance, Oldani [28] of Ingersoll Machine Tools developed a secondary compaction arrangement controlled directly by a pneumatic actuator, which enhances post-pressing fidelity and tackiness at an acceptable feed rate. To enable alternate bidirectional laying for variable-thickness structures without a cutting mechanism, Sorrentino[20] introduced a fiber placement cell that includes an integrated deposition system with two compaction units. Zacchia et al.[32] presented design guidance for calculating the curvature of a hard compaction roller profile, which impacts stress distribution, with a force/torque sensor measuring the forces and torques of a nip point, and the collected data utilized to analyze and control the bonding degree. The process accuracy in industrial robots was proposed to be

improved by Ojeda et al.[33] through a hybrid control method based on the finite element analysis of the compaction pressure.

The selection of roller material is crucial as it impacts the thermal transformation and the final consolidation process of composites [34]. For instance, steel has excellent heat conduction properties and is the most common material used for thermoplastic composites, enabling high consolidation temperatures and complete curing (autoclave curing). In the case of thermoset composites, the compaction roller compresses the fiber to the previous layer or mould and also reduces the porosity content. A flexible roller offers a more uniform laying pressure and is useful for conforming to complex mould surfaces, but its flexibility must be carefully controlled to avoid negatively affecting the fiber tows during passive energy release[35]. Some of the studies also show that due to the deformation of the roller while applying pressure there will be two nip points which will affect the size of the nip point area.[36] Thus, innovative mechanical design theory and manufacturing processes should be considered to achieve precise force control in compaction mechanisms.

Several studies have investigated defects in the layup performance of laminates in AFP systems, and the design of the AFP head layout has a significant impact on this and it is closely related to the compaction systems and also layup trajectory planning. These studies, including references [37], [38], have identified various defects such as tow misalignment, buckling, twisting, and pull-up, as shown in Figure 2-4. Addressing these issues can potentially reduce production costs and simplify maintenance.

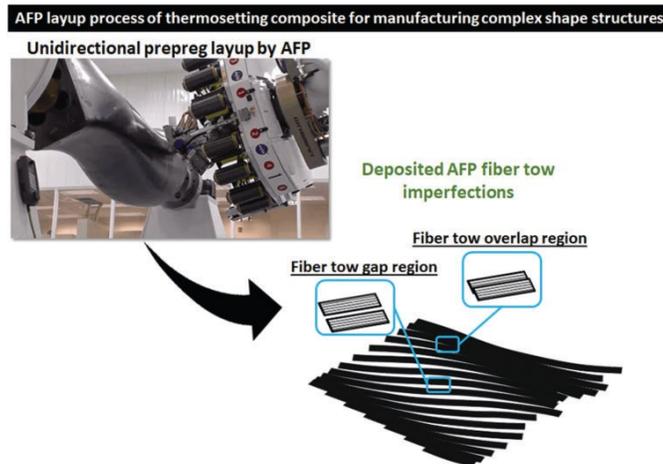


Figure 2-3 Deposited fiber tow imperfections that occur during AFP manufacturing [37]

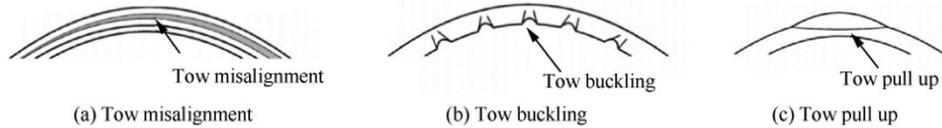


Figure 2-4 Most common tow steering defects [7], [14]

2.1.2.5 Heating systems and tow temperature

Various heating devices are available that can significantly affect the control of all process parameters. In the case of deposition of thermoplastic tows, temperatures above the melt temperature (usually 400°C) are necessary to promote molecular interdiffusion and achieve good interlayer bonding. On the other hand, for a thermosetting matrix, the process temperature should not exceed 60-70°C to prevent the onset of the cure reaction within the resin [35] which is the main reason that no heating system has been implemented in the proposed AFP head. There are different methods of Heating systems such as Ultrasonic[14] vibration, infrared heating, Laser, induction, resistive, heated tooling, and hot gas using a gas torch. Thermoplastic AFP systems often utilize the gas torch heating method, which directs heat to the nip point of the compacting roller. This method is effective in achieving the required temperature; however, it is complex to control and results in excessive energy waste, which are its drawbacks[39].

For the thermoset material besides cooling the substrate to be deposited, there is a need of using a cooling chamber to cool down the tapes due to their stickiness. For instance, the Study conducted by Shirinzadeh et al. [40] shows that they cooled down the tapes in the cooling chamber (Figure 2-5) to 5°C to reduce the tackiness of the tows and then they used rollers and spools to guide the material to the tip of the head.

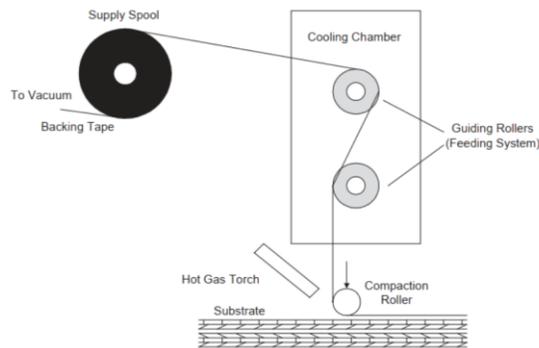


Figure 2-5 Fiber Placement head assembly[40]

2.1.2.6 Overview and Future of AFP

According to Zhang et al. [14], their objective was to present the potential opportunities in the AFP mechanism design and optimization by which the weight, cost, overall volume, and less workspace. They believe that mechanical design and optimization theory can be used in order to design an AFP with fewer numbers of actuators.

AFP technology is a promising manufacturing automation process that can support a variety of materials and conditions. However, challenges remain in the areas of system and controller design, laying speed and quality, and mold geometries. To address these challenges and promote the development of automated composite manufacturing processes, a collaboration between industries and academic institutes is necessary [14].

One solution to achieve a highly sustainable process for customized and personalized AFP mechanisms is through modular design methods. This allows for system reconfiguration and a short design-to-product cycle by module identification, interface evaluation, and module configuration. Another solution is to improve the robustness of the AFP process and increase productivity by exploring effective programming and novel design methods[14].

Additionally, further research can be conducted to increase the span of AFP system functions and layup precision, such as adjusting multiple materials with various specifications on the same equipment with high precision and improved adaptive capability. The use of multi-mode sensors based on AFP mechanisms can also aid self-diagnose and identify problems during the fiber transmission process. The integration of sub-mechanisms with self-regulating/protecting functions and control strategies is also expected to solve fundamental problems [14].

Lastly, combining multi-functions or tasks to accomplish integrated multi-manufacturing processes and assembly using a flexible manipulator can increase reliability and adaptability. The development of adaptive-controlled layup heads combined with multi-sensors is expected to reduce production costs and mitigate defects in fiber performance during the laying process[14].

2.2 Path planning and simulation

According to the survey conducted by Li et al. [41], to successfully execute the robotic fiber placement process, several essential modules should be included in the software:

- Path planning: This module generates the placement paths based on the width of the tow, geometry information of the structure surface, laying direction requirements, and the number of layers. The generated paths must cover the component surface with minimal gaps and overlaps between the tows.
- Post-processing technology: This module converts the path planning data into robotic movement instructions and provides cutting/restarting information about the fiber tow during the RFP.
- Robotic fiber placement simulation: This module simulates the laying process using the generated trajectory, robotic paths, and component surface.
- Real-time laying: This module executes the fiber placement using the robot's trajectory data and the fiber tow's cutting/restarting information.

Path planning is a fundamental aspect of the robotic fiber placement process, and it is a critical technology for CAD/CAM software. The accuracy and efficiency of the placement depend on the results of the path planning. The survey paper [41] summarizes the various path-planning methods used in robotic fiber placement.

It is also worth mentioning that there are basically two path-planning methods that are developed for robots:

- Robot offline programming (OLP)
- Robot online programming

Off-line programming is a method for planning and simulating robot manipulation strategies and creating application programs using CAD-based software on a remote computer. With this approach, the user can perform simulations without the need for access to the physical robot or workspace, which can help reduce errors and increase efficiency in programming and implementation [42], [43]. For instance, Shrinzadeh et al. used the off-line programming operation

for robotic fiber placement which shown in Figure 2-6, then they designed the work cell layout is to specify the positions for the robot and other devices. A CAD-based software program has been used for designing the parts and they matched them with the actual device dimensions. After the models were developed, the robot has been programmed to perform specific tasks, including generating a fiber path.

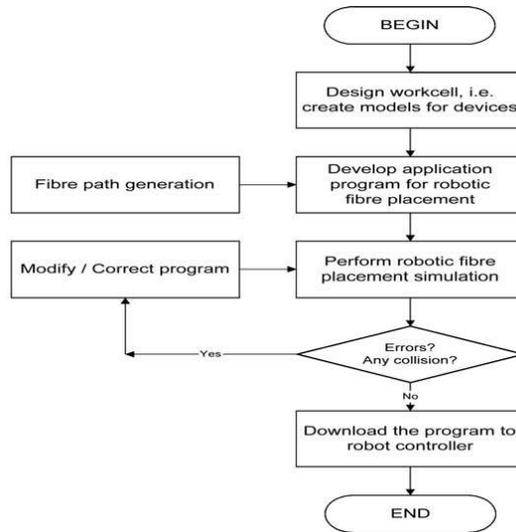


Figure 2-6 Algorithm for off-line programming of robotic fiber placement operation[43]

After the programming stage, a simulation has been conducted to verify the process. However, errors may occur during simulation due to programming errors, collisions between the robot and other devices, or encountering unreachable points. To correct these errors, modifications to the original program have been made. After the program is modified and verified, it has been downloaded to the robot controller in its native language to perform the task.

In the following path planning methods will be elaborated more.

2.2.1 Path planning methods for Fiber Placement

The goal of path planning in the robotic fiber placement process is to determine the trajectory that the robot will follow, the number of fiber tows, and the gap and overlap between them, based on the component's surface geometry, precision requirements, and layer direction. This involves several specific tasks, such as ensuring that the tangent vector of each point in the laying path

conforms to the desired layer direction to meet mechanical engineering properties, keeping the length between the tows within the allowed maximum tow width while still maintaining component forming accuracy, and obtaining the normal vector of the structure surface to control the pose of the placement head and ensure it remains perpendicular to the surface. Path planning methods are typically divided into two categories[41]: fixed angle and variable angle algorithms, based on whether the fiber laying angle changes. The fiber laying angle is the angle between the direction of the fiber tow at a given point and a reference line. If the angle between the laying path and the reference line remains constant, the algorithm is referred to as the fixed angle path planning method. If the angle changes, the algorithm is called the variable angle method. There should be noted that the above-mentioned division is due to the assumption that the layers are being deposited on simple shapes. Hence, there is another division for the complex structures such as the inner surface of V-shape structures in this situation where there is no other way than rotating the robot and changing the perpendicular normal vector to an angular normal vector.

2.2.2 Fixed angle path planning

In general, the fiber tow is positioned at a specific angle, and the angle at which it is laid is determined by the reference line. When the path is parallel to the reference line, it is referred to as the 0-degree path. On the other hand, when the path is perpendicular to the reference line, it is referred to as the 90-degree path. The reference line can either be straight or curved [44]. The initial reference line needs to be created according to specific rules, after which the remaining paths are generated based on the reference line, as depicted in Figure 2-7. The most common laying angles are 0°, 45°, 90°, and 135°.

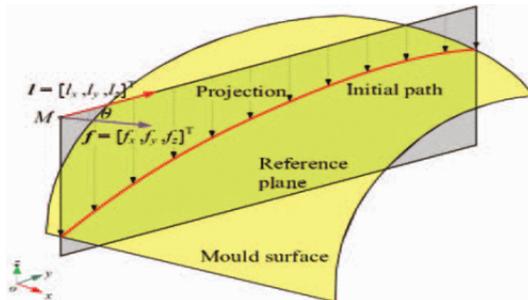


Figure 2-7 Diagram of the fixed angel path planning[44]

2.2.3 Variable angle path planning

The fixed angle path planning algorithm is relatively simple to design and implement. It can meet general strength and technology requirements. However, it does not fully utilize the potential performance of the fibers. On the other hand, the variable angle path planning algorithm has become a hot topic in research papers such as [38], as it allows for more optimized fiber placement. For example, Lopes et al. [45] used the variable angle fiber planning algorithm to design a variable stiffness composite laminated board, which applied the continuous fiber curve to practical applications. In this algorithm, the fiber laying angle continuously changes during the RFP process. The laying angle is defined as the intersection angle between the direction of the fiber laying and the x-axis, and it changes throughout the process. This approach offers several advantages[41], such as modifying the distribution and intensity of layer stress to avoid stress concentration, adjusting the natural frequency of the layer to prevent resonance phenomena, reducing the gap and overlap between tows on complex surfaces using a suitable path planning algorithm, and achieving improved mechanical properties of laminated structures by overlaying different layers with varying mechanical properties.

2.2.4 Nonprocedural Variable angle path planning

As it has been discussed earlier, all of the aforementioned division is based on the assumption of applying the pressure perpendicular to the surface. However, for V-shaped structures, this is not feasible and no literature has been found on laying up the prepreg fibers onto the inner surface of a tight corner. The main reason is that the objective of the commercially available robot is not to deposit the fibers on V-shaped structures and it is not feasible for most of the research centers to test and build AFPs that is capable of doing the mentioned procedure. Due to the lack of literature and research, an objective was set for the proposed research to develop a small-size AFP capable of depositing the tow onto the inner surface of V-shape structures.

Rotating the part before the collision is necessary to achieve the objective, making the current path-planning procedure non-procedural. However, it should be noted that this method may result in reduced pressure from the compaction roller. As a solution, it is suggested that in future work, the mould should be rotated using a separate robot rather than being fixed on a workbench.

2.2.5 Simulation

It is clear that there is a pressing need of doing simulations in the simulation environments before extracting the path to the robot in order to ensure the safety of the operator and equipment.

Specific simulation software packages are available for different robotics companies such as RoboGuide for Fanuc, and Robo studio for ABB. RoboDK [46] is a software package that provides a simulation and offline programming environment for industrial robots. It allows users to create 3D models of their manufacturing environment and simulate robot movements and tasks. The software supports a variety of robot types, including articulated, SCARA, Delta, and more, from major manufacturers such as ABB, Fanuc, Kuka, and Universal Robots. It also includes a library of robot models and tools for generating robot programs in various programming languages. RoboDK is commonly used in industries such as automotive manufacturing, aerospace, and electronics assembly to improve efficiency and accuracy in robot programming and deployment. For instance, Pieskä et al. [47] utilized the RoboDk to do research on the simulation of collaborative robots for small-scale manufacturing. RoboDk also offers a collision control feature which has been used in the research conducted by Sivasankaran et al. [48] in order to have a collision mapping planner for the simulation of Robot kinematic motions. Hence, RoboDK has been used in the proposed project in order to check the potential collision of the algorithm and finding the minimal inner angle for V-shaped structure.

2.3 Summary

Firstly, this chapter presents a literature review of various types of AFP machines and the machines which are currently available in the industrial market. Then a survey of the mechanism and essential components and systems has been introduced. Secondly, some literature review has been done in order to know different path planning methods and the proper simulation software package to test and achieve the objective of the proposed project. The next chapter presents the mechanical and electrical system design and implementation.

Chapter 3

3 Mechanical and electrical systems design and implementation:

3.1 Introduction

In order to design the AFP head first of all, all of the design constraints should be considered. Based on the constraints, some subsystems should be chosen, and in order to have a sufficient cutting system and guiding system, some improvements should have been done which led to redesigning some of the parts.

Like other robotics systems, this system also requires the proper electrical system to function properly. Hence, there is a need to identify electrical requirements like the functional voltage and current consumption for each mechanical system.

3.2 Mechanical System

In this section, the design constraints of mechanical systems will be stated and redesign of the mechanical system will be described to meet the constraints.

3.2.1 Design constraints

There are some design constraints in the project which have been stated below:

- 1) The maximum allowable payload of the FANUC M-20iA robot arm is 20 kg.
- 2) The material used in the process is a Thermoset prepreg which is a tow with a width of 1/4". Hence the machine should be able to work with a single tow of the aforementioned material.
- 3) One of the objectives which have been mentioned previously was to build and design a small AFP Head whose final dimensions should be approximately 1/4th to 1/6th of the size of the existing thermoset AFP head which is currently available at Concordia's composites lab.
- 4) The systems are required to be able to operate on flat surfaces and the inner surface of V-shaped parts.
- 5) Controls of the subsystems in the AFP head must be seamlessly integrated with the control of the Fanuc robotic arm (PLC) in order to ease the control of the whole system.
- 6) since thermoset layers which are supposed to be deposited are sticky, there is a need to have a cooling system to cool them down.
- 7) since the main objective of the project is that the AFP head should be able to print on the inner surface of the V-shaped parts the design should be optimum and small enough.
- 8) since the tapes have a non-stick membrane connected to them, there should be a mechanism to separate them from the thermoset layers and at the end collect them all.
- 9) There is a need of having a compaction system to provide the required tension and force to make the thermoset layers stick on the part.
- 10) For each cycle, there is a need to cut the layer and then feed them back again to some point under the roller for the next cycle.

3.2.2 Mechanical subsystems

This section of the research focuses on the technical aspects of designing an Automated Fiber Placement (AFP) head. It covers the four functional sub-systems of the design: tow tensioning and feeding, cutting, compaction roller, and FANUC robot arm. The aim is to outline the tools and techniques that can be used to design each sub-system effectively.

3.2.2.1 Tow Tensioning and Feeding Systems

The following section outlines the tensioning subsystems and the feeding system in order to feed the tow to the tip of the AFP head. The tow tensioning system should be installed at the top

of the AFP head between the main spool and before the feeding system. And the feeding system should be placed after the tensioning system in order to force the tow to come down and be positioned under the roller.

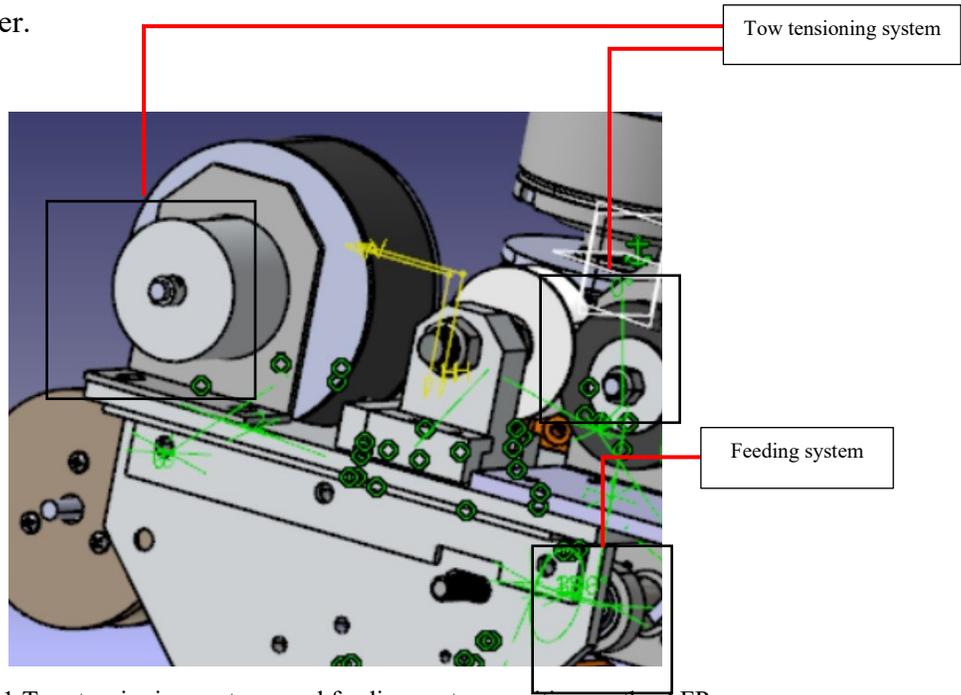


Figure 3-1 Tow tensioning systems and feeding system position on the AFP

3.2.2.1.1 Tow Tensioning System

When the tape is being drawn from the main spool, slack in the tow will occur. In order to prevent slack in the tow from becoming entangled and to ensure easy and effective feeding, the tension of the tape must be regulated. This is achieved by using two torque adjusters, one on the spool hub and the other on one of two guide rollers. The tension limiters used on the thermoset head in Concordia's composites lab were M2.5 Precision torque permanent magnets made by Warner Electric.



Figure 3-2 M2.5 Precision torque permanent magnets made by Warner Electric[9]

As the fiber tape moves through the guide rollers towards the feeding system, the backing is directed towards the backing spool attached to the plate of the head. A friction drive is necessary to ensure slip between the motor and the backing spool, and this is achieved by mounting a DC stepper motor on the backing spool with a drive coupling that allows slipping. The motor used in Concordia's lab was a brushed DC Gearmotor (GM9236S014-R1 AMETEK Pittman) with a power supply of 24 VDC.

In the proposed project, a novel design has been implemented. Figure 3-3 shows the 3D printed spool that holds the fiber tow and is a crucial part of the main spool system. The spool is connected to a magnetic particle clutch that acts as a brake and provides tension to the fiber tow. This clutch allows precise control over the amount of tension applied to the tow fiber while preventing the spool from unraveling uncontrollably. This design ensures that the fiber tow is dispensed in a controlled and consistent manner, which is important for the quality of the final product.

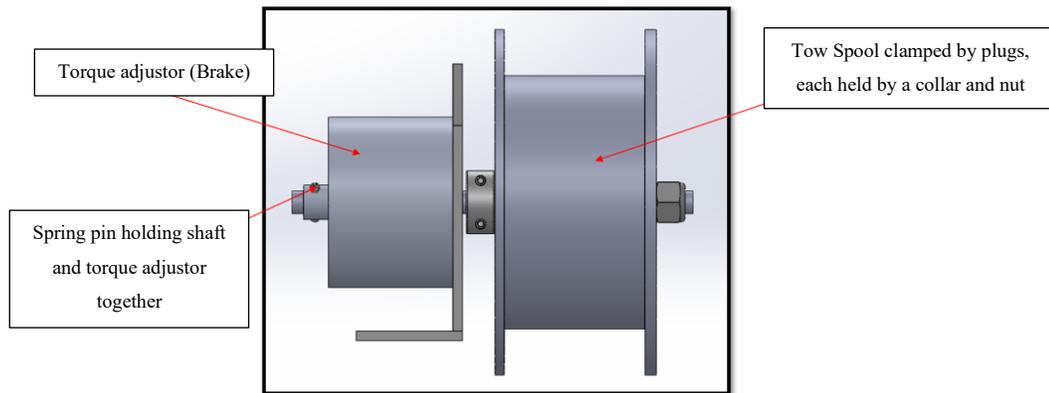


Figure 3-3 Tensioning system on the main spool [9]

The system for tensioning the tow consists of two assemblies: a T-shaped mount assembly and a rubber idle roller assembly, as shown in Figure 3-5. The first assembly comprises a guide roller attached to a T-shaped mount that allows some lateral movement using a screw. The second assembly is connected to the first one through a flexible TPU idle roller that is compressible and provides friction when in contact with the tow. This roller is connected to a magnetic particle clutch, enabling torque adjustment and tension control for the tow being fed through the system.

The system design depends on two Warner Electric magnetic particle brakes, labeled as torque adjusters T1 and T2, which can each provide adjustable braking torque ranging from 0.00353078 N.m to 0.155354 N.m [9]. The range of achievable tension levels can be observed in Figure 3-4 as the settings of the torque adjusters are adjusted.

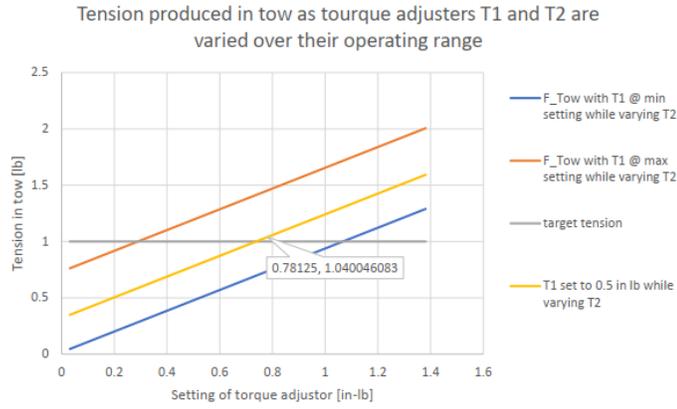


Figure 3-4 Tension produced by Torque Adjustors[9]

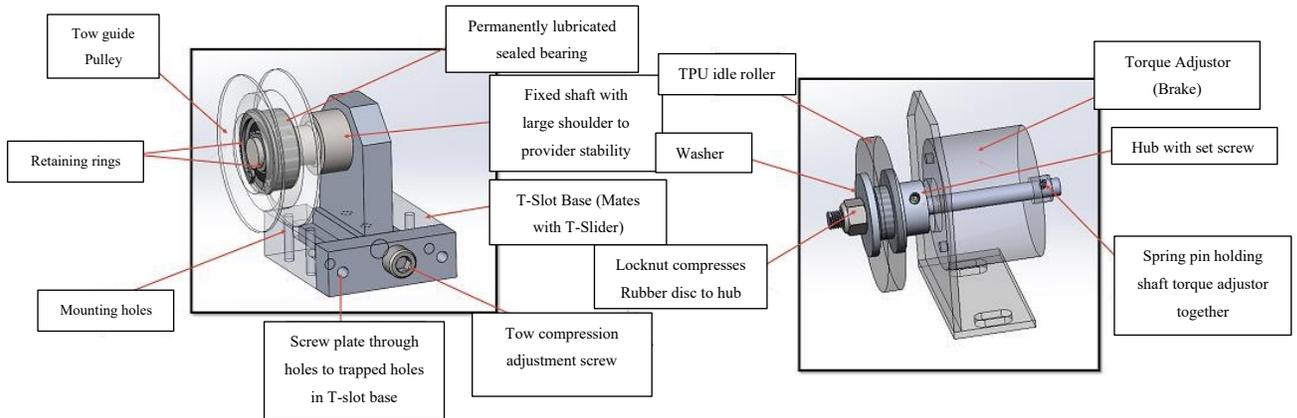
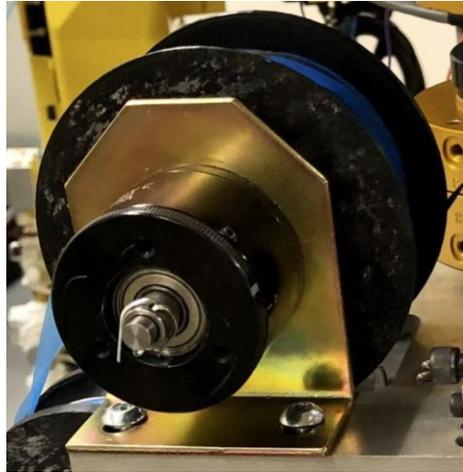
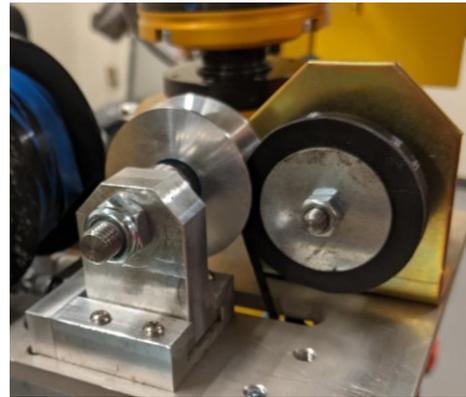


Figure 3-5 Tensioning system design[9]



a)



b)

Figure 3-6 a) Main spool b) Tow tensioning system

3.2.2.1.2 Tow Feeding System

The tow used in process consists of two components. The first component is a black fiber-reinforced composite that is applied to the workpiece. The second component is a thin blue plastic backing membrane, which lines one side of the composite material. This backing membrane is designed to provide a surface that is less adhesive, allowing the tow to be rolled on a spool without sticking to itself. A visual representation of the tow has been provided earlier in Figure 1-8.

The feeding system of the thermoset head consists of two feed rollers, a drive roller, and an idler roller. There are two options for driving the tow in the feeding system. The first involves using a pneumatic actuator to engage and disengage the idler roller from the tow. The second option involves replacing the actuator with a sprag clutch or one-way bearing, which allows the tape to be pulled through the guide rollers of the tensioning system when the drive motor is not running. The drive roller of the feeding system can be powered by a DC stepper gearmotor, and the thermoset head in Concordia's AFP lab used knurled drive rollers and softer material, such as silicon rubber, for the idler rollers.

The feeding system in the proposed project is composed of two assemblies: the sprag bearing assembly and the idle roller assembly, as shown in Figure 3-7. The sprag bearing assembly

includes a Nema 17 stepper motor, a coupler, and a sprag bearing wrapped with adhesive grip tape to increase friction between the tow and the bearing. The sprag bearing allows unidirectional motion and the coupler joins it to the stepper motor. The idle roller assembly uses a bearing with a urethane-coated roller that can compress. The two assemblies are connected using a slot on the structure plate, which allows for adjustability.

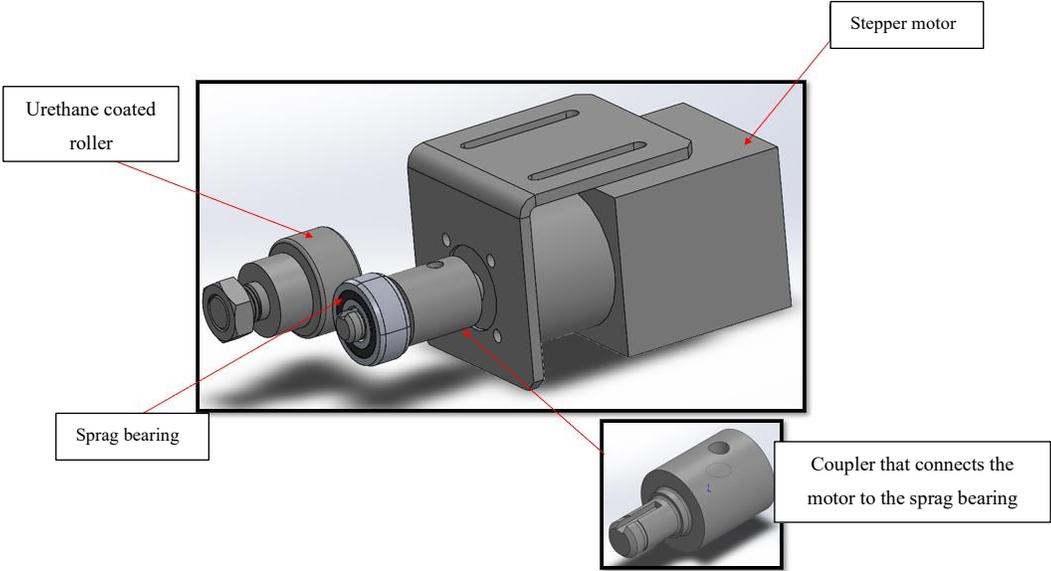


Figure 3-7 Feeding system design[9]



Figure 3-8 Feeding system [9]

3.2.2.2 Cutting System

In order to detach from the workpiece and execute multiple plies, a cut must be made as the tow is fed from the material spool to the compaction roller. To ensure a clean cut, it is important to maintain the orientation of the tow in the guide it entered and avoid any twisting, which could

cause problems and affect the result. This can be achieved by tensioning the fiber carbon reinforced plastic tow and using a high-speed, sharp, and thin blade that moves towards a fixed blade. The mechanism functions similarly to scissors and effectively cuts through the material without it sticking. Achieving a clean cut depends on finding the optimal balance between force, speed, and a sharp metal blade. The angle of the blade also plays a role in enhancing its effectiveness, as a slanted edge reduces contact area and facilitates cutting through the material. This feature can be leveraged to minimize the reaction force of the blade. It is worth mentioning that the cutter position is under the feeding system as mentioned in the following Figure 3-9.

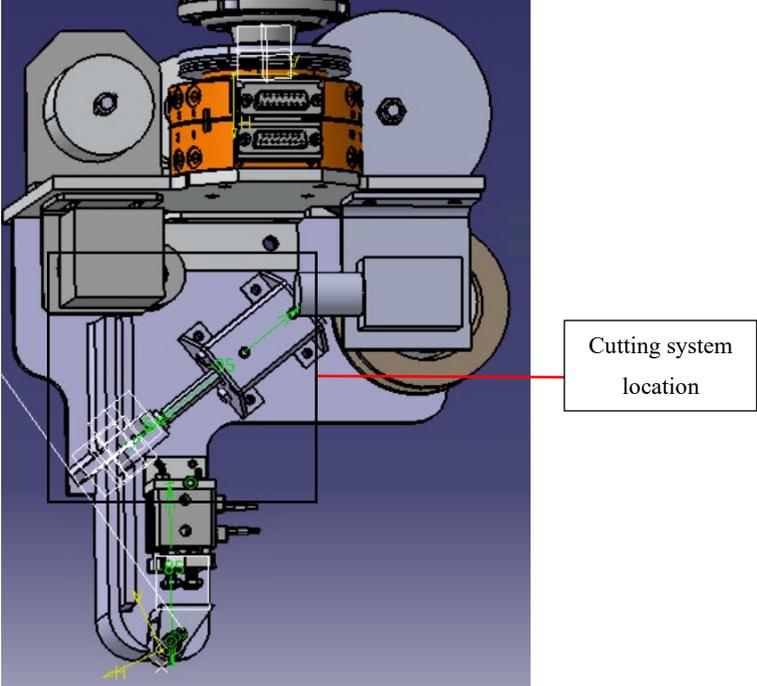


Figure 3-9 Cutting system location

A CDQ series 16mm bore non-rotating rod pneumatic actuator with a 20mm stroke is used to actuate a dynamic blade and serves as the driving force for the cutting system. The actuator, manufactured by SMC, is secured to the Vertical Side Plate through a manufacturer-provided bracket, as shown in Figure 3-10.

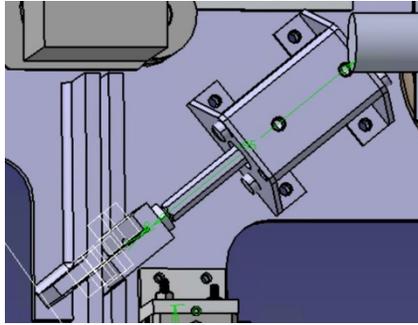


Figure 3-10 Cutting system

3.2.2.3 Compaction Roller System

The compaction roller system is a mechanism used in automated fiber placement (AFP) to compress and adhere the fiber material, such as carbon fiber, to the surface of the workpiece. It typically consists of a roller with a controlled pneumatic system, which applies a specific amount of force to the fiber material passing underneath it. The amount of pressure applied by the roller can be adjusted based on the requirements of the specific application. The compaction roller system is an important component of the AFP process, as it helps to ensure that the fiber material is properly adhered to the surface of the workpiece, leading to consistent and high-quality results.

To ensure that the tow can be applied to flat surfaces and various shapes without obstruction, the compaction roller system's nip point must be kept free from obstructions and designed to be as small as possible. To prevent damage to the workpiece during compaction, a soft material such as silicone should be used for the roller. This will allow for safe pressing by the robotic arm, ensuring the tow adheres to the workpiece and providing flexibility in the vertical movement of the FANUC arm. The compaction system is placed at the bottom of the AFP head and the roller is the lowest part of the whole AFP head.

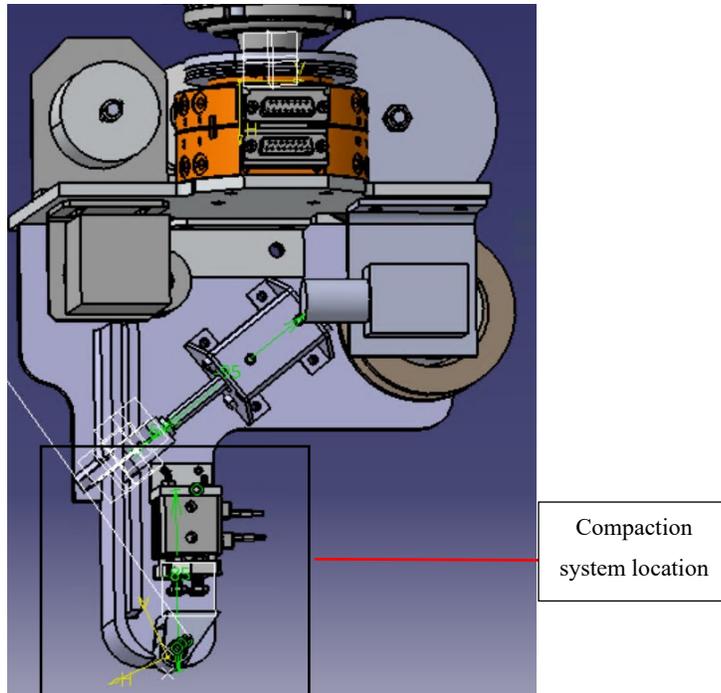


Figure 3-11 Compaction System location

The compaction system in the proposed model uses an SMC pneumatic cylinder with a 16mm bore and a 10mm stroke, capable of providing a compaction force of 40-140 N depending on the air pressure supplied. After doing multiple tests, it turned out that 40N is sufficient to provide adequate pressure in order to adhere the tow to the workpiece. The cylinder is attached to the Vertical Side Plate via the Actuator to Chassis Bracket, as shown in Figure 3-12. The force is delivered to the tow via the Actuator Faceplate to Roller Bracket and Roller, which was designed to accommodate flat surfaces and can be modified as needed. The components were designed using steel to ensure an infinite lifecycle and the Compaction Roller is made of 40% Glass-filled Nylon and can be easily replaced by other materials if needed.

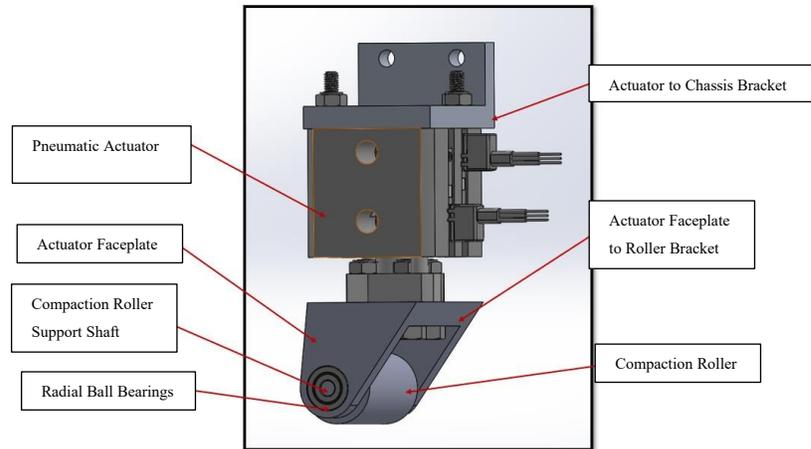


Figure 3-12 Compaction system[9]

3.2.2.4 Guiding system

The guiding system includes the cutting and cooling systems and extends from the end of the feeding system to just before the nip point of the roller and compaction system. Its purpose is to provide a surface on which the tow can lie, be cut, and then be guided precisely under the roller for each sequence. The material of this system will be discussed in the cooling section.

3.2.2.5 Membrane collector system

The blue membrane attached to the tow should be disconnected before cutting and depositing the material, and a brushless DC motor is used to collect the membrane during each deposition sequence. After collecting the membrane and getting full, it should be disconnected and the collected membranes should be thrown away, and then the system should be re-mounted. The system is also coupled with a torque adjuster that can be adjusted to prevent tension and rotate the main spool in the reverse direction. This system is positioned under the main spool and the membrane is separated from the tow from the main spool it will be taped to the collector system, so it is capable of collecting the tape.

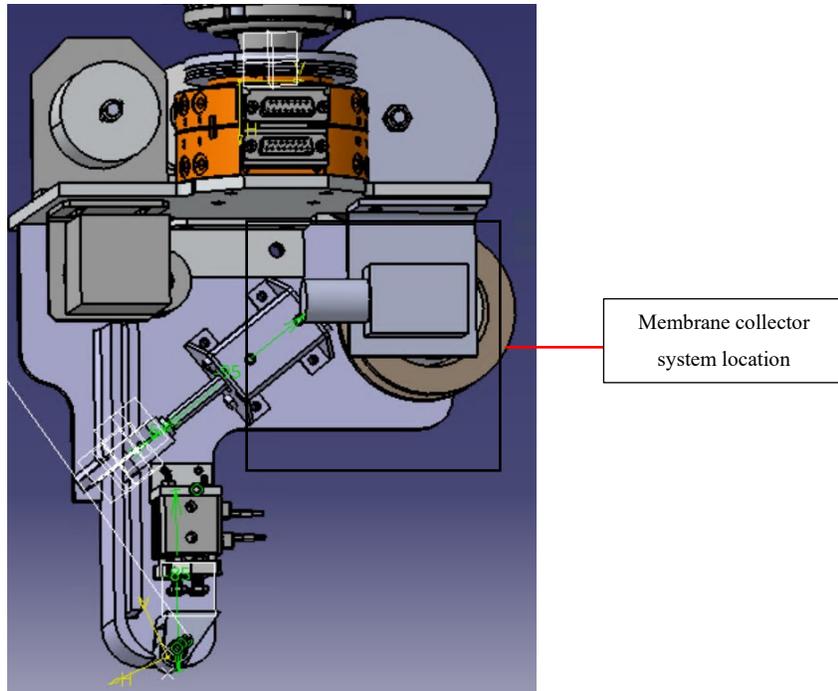


Figure 3-13 Membrane collector system location

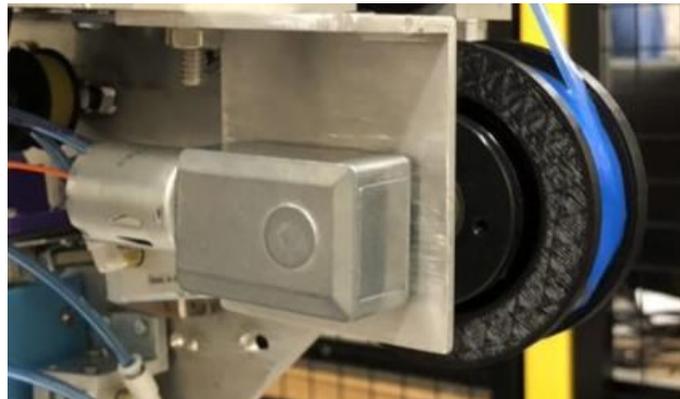


Figure 3-14 DC motor coupled to a spool of collecting system[9]

3.2.2.6 Cooling systems

Since the tow is sticky and the removal process of the membrane is before the cutting and depositing it stick to the surface of the guiding system as discussed earlier. The cooling system is located in between the cutting and guiding systems, and it ensures that the tow remains free from

any obstruction before reaching the compaction roller. To avoid it, a unique cooling system has been implemented which will be discussed in the following thoroughly.

3.2.3 Redesigning the cutting and guiding systems

Since the project was started by a group of undergraduate students as their capstone project there were some issues with the cutting system which were partly caused by the guiding system. After the proposed project has been started, it has been realized that the whole design requires to be changed. Hence, brainstorming was immediately started, and the work on the design started again. Fitting all the components back on the robot to initiate the rapid prototyping stage has been also started. Throughout this stage, different 3D printed parts have been manufactured in order to ensure that the new design works. Eventually, a design featuring a functional cutting and the guiding system were developed. The guiding system was completely redesigned and incorporated into the side plate to simplify assembly and enhance durability. Meanwhile, the cutter was completely replaced with a new system featuring two blades spaced 0.25mm apart and angled at 80 degrees. When the pneumatic system is activated, the blades act like a scissor, resulting in a clean cut. Other changes include changing the compaction system, repositioning the systems, reducing the spaces between each system, adding a cooling system, and introducing a new and unique guiding system. The previous cutting system was using a fixed blade and a dynamic blade where the dynamic blade was pulling the tape toward the other blade and the tape was constantly moving whereas in the new approach, a razor blade have been positioned on the guiding system and the other razor blade pushes the tape to the other blade which acts like a scissor. This prevents the tape from moving and sticking to the blade.

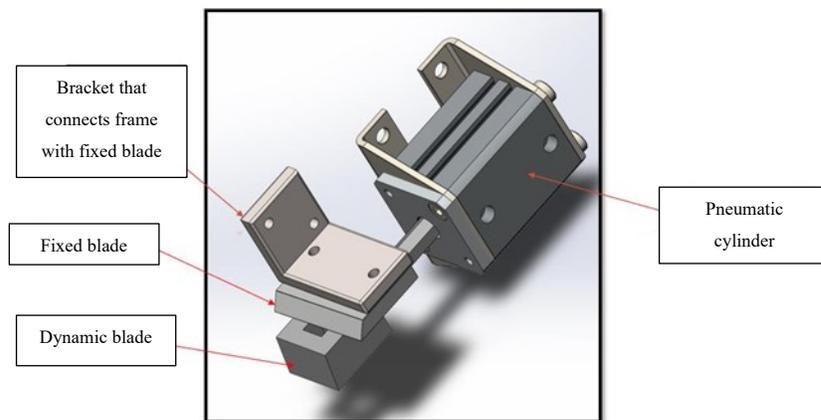


Figure 3-15 Capstone project cutting system design [9]

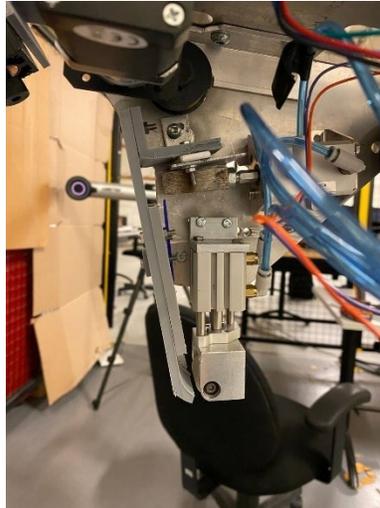


Figure 3-16 Previous cutting system [9]

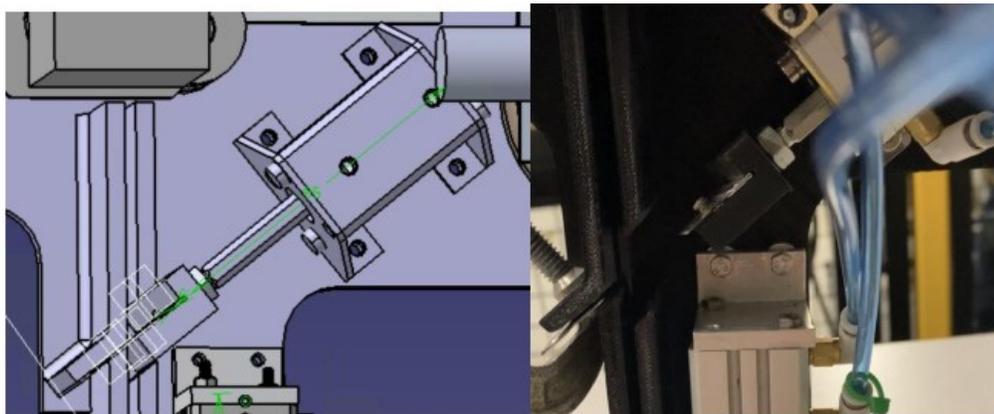


Figure 3-17 The redesigned version of the cutting system

3.2.4 Cooling system methods

There are a couple of ways to cool down the tape to avoid its stickiness. Here, some of the potential ways are discussed.

- **AirJet**

Airjet is a system working by blowing a stream of cool air onto the object or area that needs to be cooled. The cool air removes heat from the object, lowering its temperature. Since this machine was available in the Robotics lab, in order to assess the feasibility of integrating an AirJet cooling system into the robot's design, some attempts have begun to use the AirJet and perform a preliminary evaluation of its functionality. After consulting manuals for newer versions of the

AirJet as a reference, some tests have been eventually done that showed the Airjet machine is capable of achieving temperatures as low as -60 Celsius.

However, difficulties were encountered in attaching the AirJet to the robot's head due to its large size. To address the issue, the possibility of acquiring a longer tube that could be connected to the robot's head while the AirJet was kept on the ground was explored as a potential solution. Regrettably, this approach was ultimately considered unfeasible as the tube tended to freeze and become brittle at temperatures as low as -5 Celsius, impeding its ability to bend as required to connect with the robot's head.



Figure 3-18 Air jet system

- **Peltier Modules**

In order to overcome the thermodynamics challenge, Peltier modules have been chosen. These are small thermoelectrical modules that upon providing the proper voltage, one side gets hot and the other one gets cold. These devices work on the temperature difference principle with a positive temperature coefficient. As the energy applied increases, the temperature difference between the sides gets higher, however, this means that the hot side can reach heat outputs of 5W and 40 degrees Celsius[49].

To decrease the temperature of the plates of the Peltiers, a DB04028B12U fan has been utilized which is a small size 40mm * 40mm fan with a rotational speed of 15000RPM. This fan sends the pressurized air onto the heatsink which has been mounted on the Peltiers.



Figure 3-19 Peltier, Fan, and heat sink

3.2.5 Investigation on finding a material for new guiding system

To reduce the friction between the tape and increase the conductivity of the guiding system, various materials were evaluated.

3.2.5.1 Teflon Sheet

Before testing the thermoset fiber on the Teflon sheet, lubricants have been applied to the PLA guiding system to decrease friction between the tape and the guiding system, but this approach had some drawbacks. The lubricants had residual properties that changed the mechanical properties of the tape. As a result, Teflon, also known as PTFE, has been used as an alternative material to reduce friction.

However, using Teflon presented its own set of challenges. Teflon is a harder material to work with due to its flexible and insulating nature. In order to test whether the thermoset fiber would adhere to the Teflon surface, the tackiness of the fiber on the Teflon sheet has been tested initially. The initial tests produced positive results: it has been clear that the fiber had difficulty sticking to

the Teflon surface, and the Teflon surface did not leave any residue on the fiber as the lubricants did. Overall, it has been found that using Teflon as a material in the guiding system reduced friction and helped to maintain the mechanical properties of the tape. However, low thermal conductivity has been identified as the main issue, which necessitated the use of a different material.



Figure 3-20 Teflon Sheet

3.2.5.2 Copper Plates

To address the previous challenges encountered with the Peltier modules and PLA guiding system, a new approach was taken. The outer part of the guide system was constructed using copper, which is known for its excellent thermal conductivity. By utilizing Peltier modules and handcrafted copper plates, temperatures of approximately 12 degrees Celsius were achieved.

While the achieved temperature of 12 degrees Celsius improved the tackiness issue, it has been recognized that there are potentially more effective and stable solutions for future research. The use of liquid hydrogen is one such option worth exploring.



Figure 3-21 Implementing Copper sheets in the proposed design

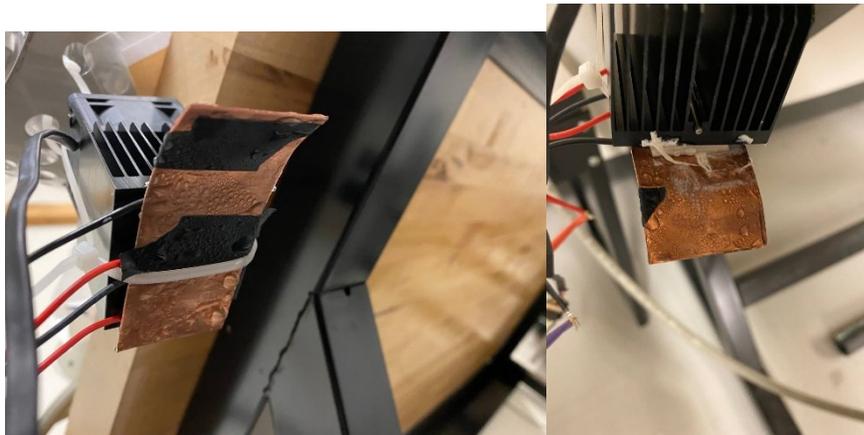


Figure 3-22 Condensation on the Copper plates

Following the assembly of the copper plates, Peltiers, and updated design, a comprehensive test was performed to assess the effectiveness of the newly implemented designs. Results indicated that the guide system was no longer adhesive (although a short-term solution), and the cutting system exhibited optimal performance as previously described, successfully cutting thermoplastics with the latest modifications applied.



Figure 3-23 Implementing Copper Plates and Peltiers in the proposed project Design



Figure 3-24 Implementing Copper Plates and Peltiers in the proposed project Design

3.2.6 Summary of Mechanical Section

The proposed project had a mechanical objective to create a functional design for the AFP head that would be more compact and efficient than the existing one in the Concordia University lab, without compromising on performance. The need for a more compact design was driven by the requirements for flexibility and maneuverability in tight spaces while maintaining a high degree of precision.

The existing AFP head, while efficient, was bulky and complex, making it difficult to operate in smaller spaces. The proposed head aimed to address these limitations and was designed with the use of advanced technologies and design principles.

In order to achieve this objective, a detailed study of the existing head was conducted, taking into consideration its specifications and limitations. The proposed head was designed with the objective of being smaller, yet more efficient, than the existing one, by making use of innovative design techniques and materials.

Figure 3-26 and Figure 3-27 provide a comparison between the two heads in terms of size. As can be seen, the proposed head is significantly smaller than the existing one, without compromising on performance. The new design provides greater flexibility and ease of operation, enabling it to be used in a wider range of applications. This fact has been discussed in the following chapter in more detail.

Overall, the successful implementation of this objective has resulted in a significant improvement in the efficiency and versatility of the AFP head, making it an important component of the proposed project.



Figure 3-25 Final AFP head

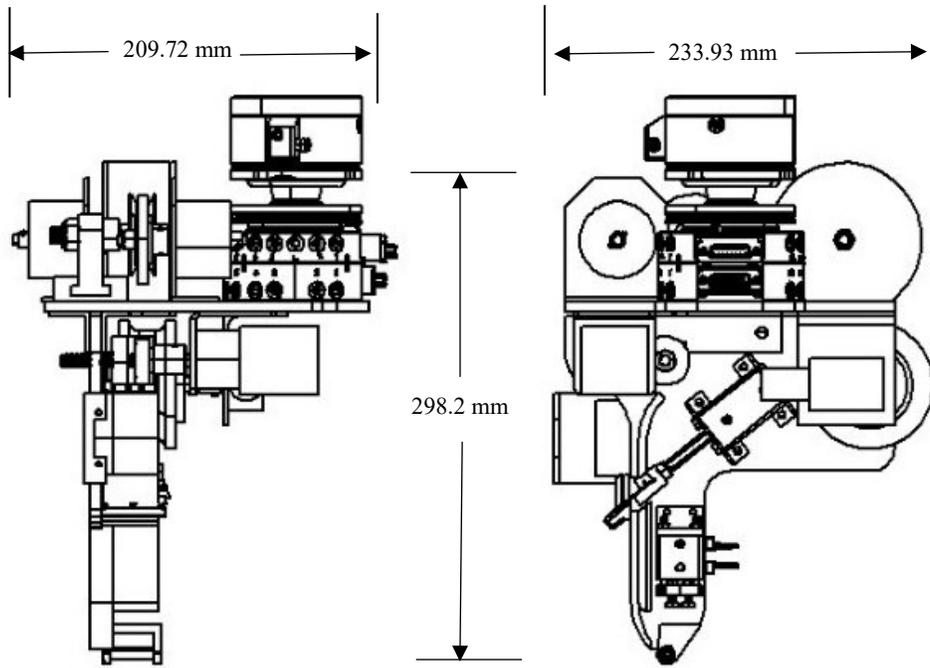


Figure 3-26 Side view and front view of the CAD design of the proposed project

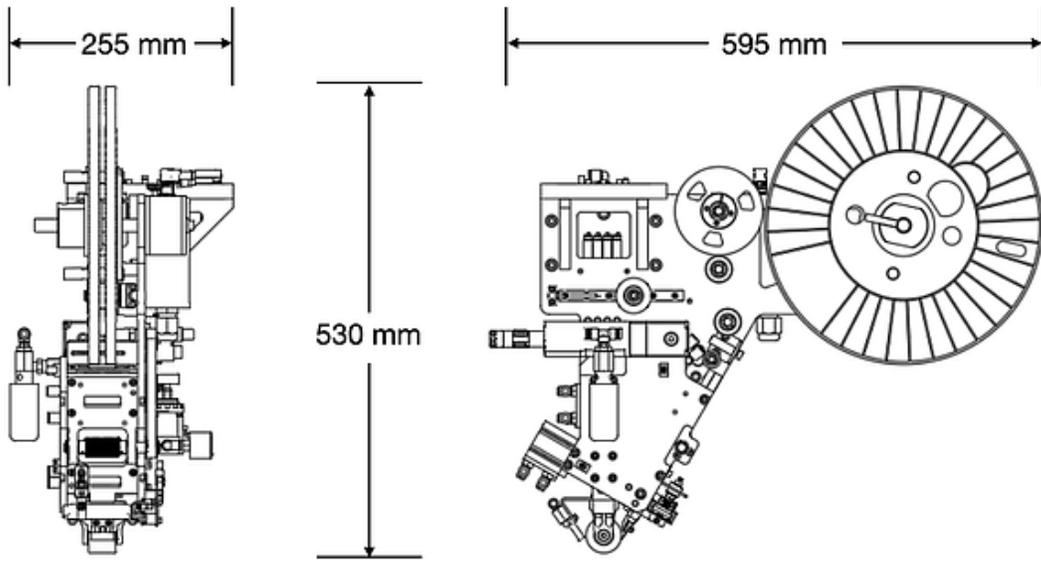


Figure 3-27 Side view and front view of Concordia University AFP head

3.3 Electrical system

After thoroughly examining the electrical specifications of the mechanical components and the pneumatic system, a list of 5 electrical units was created to ensure compatibility with the desired voltage and current levels in the electrical system. This list has been illustrated more in the following:

1. PLC of the Fanuc Controller
2. The driver which has been designed for the research including the Arduino (Driver box)
3. Serial manipulator electrical unit
4. Pneumatic systems electrical unit
5. AFP head electrical unit

The aforementioned list should be connected properly together with the consideration of the communication requirements between the PLC and the driver, as well as between the driver and the robot electrical unit, to ensure that they can communicate and exchange data effectively. In the meantime, thermal management of the electrical components has been considered, including the use of heat sinks, fans, and other cooling mechanisms, to ensure reliable operation and longevity of the electrical system.

Finally, the connections have been documented for future tests and research.

The connection schematic of the above-mentioned units is stated below.

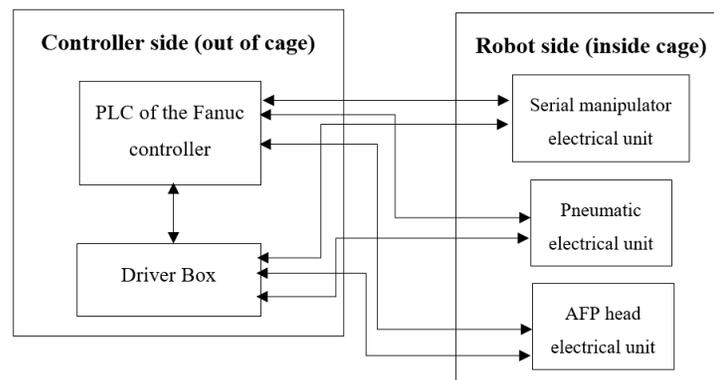


Figure 3-28 Schematic of connections

3.3.1 PLC of the Fanuc driver

The AFP head is mounted on a FANUC M-20ia robotic arm with six degrees of freedom. To perform the laying of the tow on a workpiece, both the arm and the head must be implemented together and the information can be exchanged with each other. To achieve this, the use of an AOD16D Fanuc Modular Output Module is used. The module is inside the PLC, as shown in Figure 3-29.

The Programmable Logic Controller (PLC) is a crucial component of the Fanuc driver, serving as the central control unit that manages and monitors the operations of the driver. This computer-based system uses input signals from various sensors to control the behavior of the driver and communicate with other components within the system, such as the robot electrical unit and the pneumatic systems electrical unit. The functionality of the PLC will vary based on the requirements of the specific application and the overall design of the system.

In this research, the PLC is used to receive commands from the code to turn the digital outputs on or off. The digital outputs are powered by a 5-volt voltage power unit, allowing the same voltage to pass through the output channel. Depending on the requirements of the component being powered, the output channels may be connected directly to the pneumatic systems electrical unit or the AFP head electrical unit (for low current consumption components), or connected to a relay (for high consumption systems). The relay then switches the voltage to the normally open channel to provide the desired voltage for the unit.

In addition to being controlled by the PLC, the Digital outputs in the Fanuc driver can also be actuated by a code. This code is designed to control specific actions and processes within the system. For example, when the robot is in its cutting location, the code will send a command to turn on Digital Output 2 and immediately turn it off. This action will cause the DO2 output, which is connected to the pneumatic electrical unit, to activate the cutting system's solenoid. As a result, pressurized air will be sent to the cylinder behind the cutter, causing it to move forward and then backward to complete the cutting process. In other words, to activate an actuator, the DO[X] digital output function must be used in the FANUC Teach Pendant code. This function sends a constant voltage signal of the same value as the power supply when the Output Module is powered by.

Table 3-1 Table of the PLC connections

Pin#	Pin Label	DO[X]	Actuator
2	A0	1	Compactor
3	A1	2	Tool changer
4	A2	3	Cutter
7	A5	6	Stepper Motor
8	A6	7	Servo
9	A7	8	Fan and Peltier

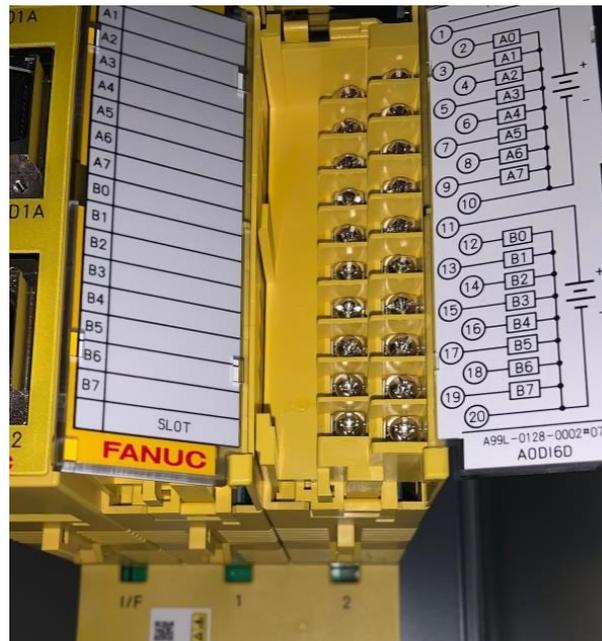


Figure 3-29 Fanuc Modular Output Module[9]

3.3.2 Driver box

To develop and design a driver box, several steps were taken. Firstly, a schematic was created to outline the required drivers, power supply units, microcontrollers, and connections. Secondly, various connectors were needed to connect the driver box to other units. Thirdly, an Arduino Uno microcontroller was utilized within the driver box to detect one of the digital outputs of the PLC and activate the stepper motor of the feeding system.

3.3.2.1 Creating a driver containing the Electrical components of the AFP

In order to have a compact driver box containing all of the electrical components a small box has been created which contains one Voltage Supply Unit (VSU) of 12V, two VSUs of 5V, a driver of the stepper motor, and an Arduino Uno. Due to the high current consumption of some of the component like Peltier and its fan, some relay switches have been also added to the box. Figure 3-31 demonstrates a Top view of the driver box.

To this end, the following features have been implemented:

- A schematic of the complete Electrical systems circuit was planned which is also useful for documenting for the future operator or researcher. The Picture of the electrical circuit has been shown in the **Appendix A**.
- It is worth mentioning that, in order to make sure that the drivers are functional and on a small LED was implemented which turns on once the driver is on.
- In order to cool down the package, a fan has been implemented.
- It is worth mentioning to make all of the connections stable, all of them should be soldered to some connector female or male to go through each other whenever it is needed. Hence soldering all of the electrical connections was a pressing need.
- In order to ensure stable connections, it was necessary to use Female and Male DB9, DB25, and DB15 connectors. The DB9 connector was used as the output from the PLC and connected to the driver. The DB25 connector served as the output from the driver and the input to the robot's internal connections. Finally, the DB15 connector was used to connect the internal connections of the robot to the tool changer, with another DB15 connector linking the tool changer's bottom side to the AFP components, such as motors, the compaction system, and the cutting system.



Figure 3-30 Driver box side view

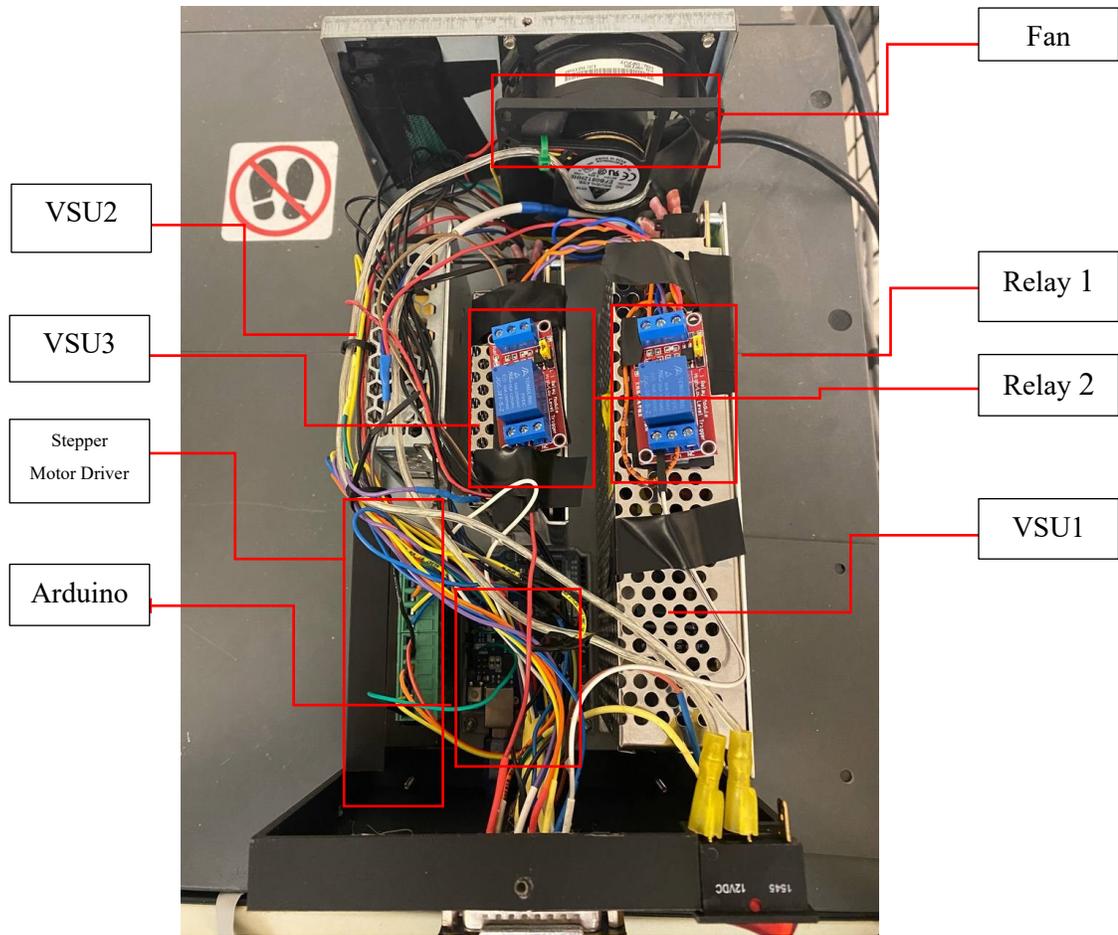
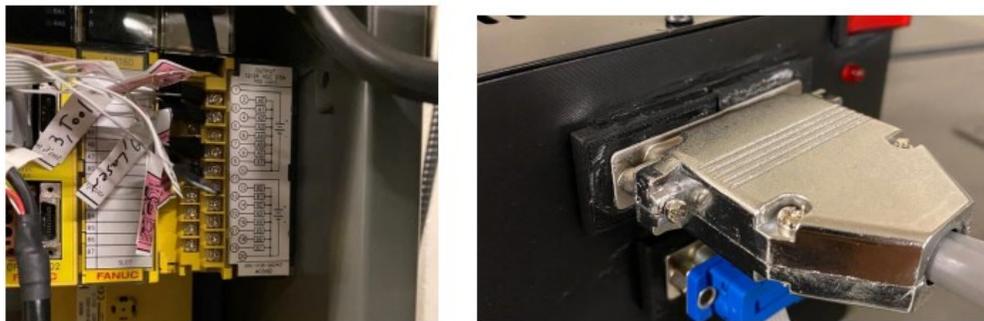


Figure 3-31 Driver box top view and components



a)

b)

Figure 3-32 a) Fanuc Modular Output Module with connectors b) DB connectors for Driver Box

3.3.2.2 Creating the new Arduino code for the feeding system

To establish a reliable feeding system, an Arduino code was developed to activate the stepper motor at the precise moment. The Arduino board is used to send a PWM signal to the stepper motor driver. The output from the PLC of the controller was connected to a pin on the Arduino. Whenever the deposition process was about to begin, the digital output of the PLC was activated and sent as an input to the Arduino. If the Arduino detected a voltage of more than 2 volts (5 volts in our case), this indicated that the specific pin was "on." When the pin was on, the code inside the loop activated the stepper motor to rotate based on calculations. Each rotation of the motor was calculated to correspond to a specific distance, which was determined by dividing the distance from the cutting blade tip to the compaction system. This allowed for the proper placement of the tape beneath the compaction system. It defines constants for PINs and sets the *stepPin* and *dirPin* as output pins in the *setup()* function. The *loop()* function waits for a specific condition before executing a sequence of 4000 steps in a specific direction with a delay between each step. After the sequence, there is a delay of 2 seconds before the code repeats. The code is available in the **Appendix B**.

Since the perimeter of the feeding system is fixed, the following equation led to having 4000 steps for the steps inside the code.

$$\text{Perimeter of the feeding system } = P = 2\pi r = 5 \text{ mm} \quad (3.1)$$

$$\text{Distance between cutting point and roller } = D = 10 \text{ cm} \quad (3.2)$$

$$\text{Number of revolutions } = n = \frac{D}{P} = 20 \quad (3.3)$$

$$\text{Number of steps} = n * \text{steps per one revolution} = 20 * 200 = 4000 \quad (3.4)$$

3.3.3 Serial manipulator electrical unit

This unit contains the Fanuc 14-pin EE cable and the connector are a specific type of connection used in the Fanuc robot system. The cable has 14 electrical pins for connecting different components within the system, and the connector attaches to the end of the cable for connecting the components to the control systems. In the project, one of the inputs of the unit is connected to

the output of the driver box, while the other end is connected to the third link of the Fanuc robot. The connector is then connected to the two units of the AFP electrical unit (10 pins) and the Pneumatic systems electrical unit (4 pins). It is important to note that the specifications of the Fanuc 14-pin EE cable and connector can vary depending on the Fanuc robot model and the specific requirements of the application.

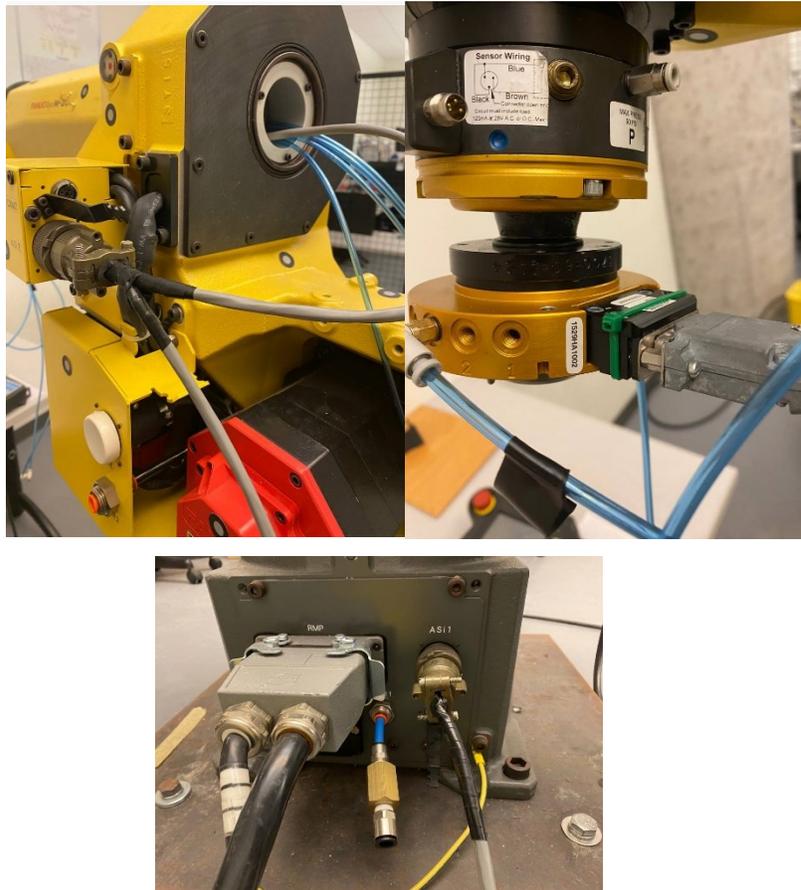


Figure 3-33 Connection of serial manipulator electrical unit

3.3.4 Pneumatic systems electrical unit

The pneumatic systems electrical unit holds the pneumatic actuators and has four output wires from the serial manipulator. These wires are 1) the input voltage for the compaction system solenoid, 2) the input voltage for the cutting system solenoid, 3) the input voltage for the tool changer system solenoid (for future researchers), and a common ground wire for all the systems.

This unit has the solenoid actuators input valve for the pressured air, a pressure relief valve, a modular style regulator, and a filter which are all labeled in Figure 3-34.

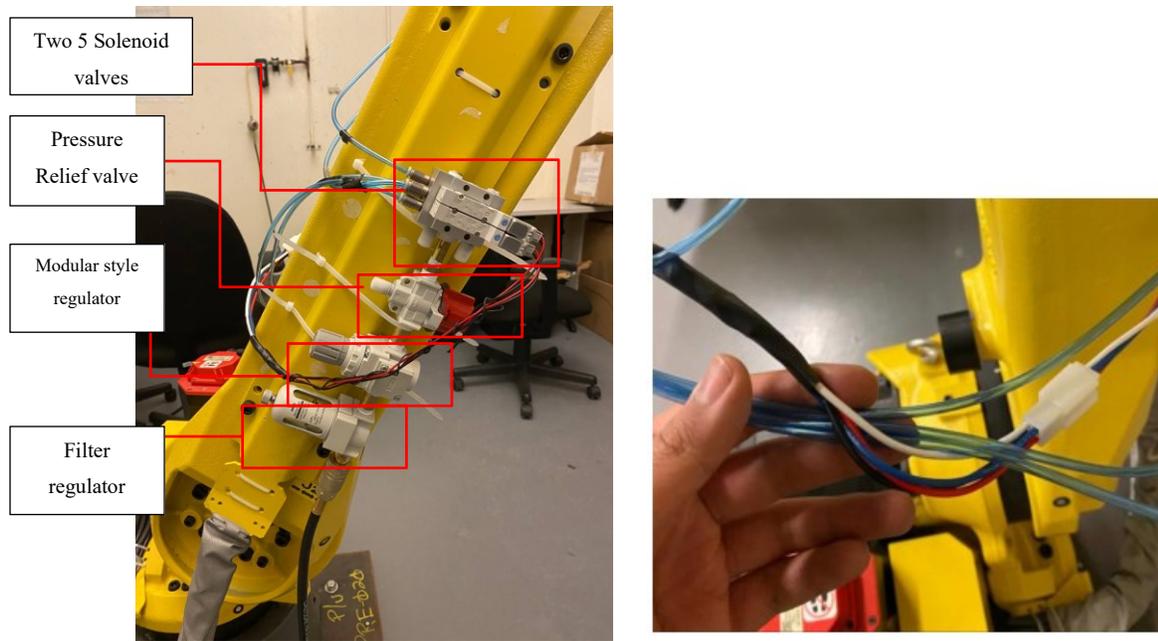


Figure 3-34 Pneumatics systems electrical unit

The pneumatic actuators in the unit work by receiving power (12 volts) and then directing pressurized air through the valves to different components such as the compaction and cutting systems, which are mainly made up of cylinders and pistons. This allows the actuators to control and activate the functions of these components.

3.3.5 AFP head electrical unit

As mentioned earlier in the mechanical section, this section has different subsystems such as Peltier with its fan, stepper motor, DC motor, cutting system, and compaction system.



Figure 3-35 View of the bottom side of the AFP head

Each of these systems requires driftnet voltage and consumption currents and actuating methods in the following the required values and connections for each of them will be stated:

3.3.5.1 Peltier and Fan

The Peltier module which has been used is a TES1-07102 Thermoelectric cooler Peltier plate with a dimension of 23*23 mm [49]. It requires a voltage of more and equal to 5 volts it is a high consumer of current when its functions hence it cannot be connected directly to the output of the PLC system due to its limits. Hence a relay has been implemented to be actuated by the Digital Output of the Fanuc PLC and then it will send the 5 volts from the power supply unit inside the Driver box to the Peltier. The following table shows the Peltier specifications.

Table 3-2 Peltier Specification

Hot side Temperature	25°C	50°C
Maximum voltage	8.1V	9.2
Maximum Current	3.2A	3.2A
Delta T Maximum	67°C	75°C
Q maximum	15.4W	16.7W

It is worth mentioning that since the Peltier mechanism makes one of the sides hot and the other cold it needs a fan to provide the required work with it all the time. Hence, due to the limitation of the voltage sources, a 5V voltage has been powered by the Peltier which according to the data-sheet is providing a Delta T of 30°C if the hard plate receives the required cubic feet per minute of air from a Fan.

In order to prevent the Peltier's hot plate from becoming very hot, a small size(40*40*28mm) fan with a rotational speed of 15000 RPM has been used. This fan requires a 12 volt as its functional voltage. This fan requires a maximum of 2 amps for its current which is not feasible to take it from the output of the PLC. Hence, another relay has been used for this which has the same input as the Peltier so they can turn on at the same time. The only difference is that the common channel of this relay is connected to 12 volts power supply unit.

3.3.5.2 Stepper motor

The stepper motor requires four wires which are directly connected to the outputs of its driver. A driver of a stepper motor is an electronic device that converts the control signals into a sequence of electrical pulses, which are fed to the stepper motor coils. The driver manages the flow of electrical current to the motor coils, thereby controlling the motor's position, speed, and torque. The driver is also responsible for micro-stepping, which is the process of dividing each full step of the motor into several smaller steps, thus allowing for more precise control over the motor's position. The choice of driver depends on the requirements of the specific application and the specifications of the stepper motor being used. Hence, TB6600 was selected to be used as the driver of the Stepper motor. The following table also shows the stepper motor driver's specifications.

Table 3-3 TB6600 specification

Operating voltage	9-42 V
Max output Current	4.5 A per phase, 5.0 Peak
Microstep resolution	Full, 1/2, 1/4, 1/8 and 1/16
Protection	Low-voltage shutdown, overheating, and over-current protection
Dimension	96* 72 *28.36 mm

It receives commands from the connected Arduino Uno and uses this information to determine the steps and rotation speed of the stepper motor. Additionally, in the project, the micro-step has been set to 1/2. The driver is connected to a 12 volts voltage supply unit, which provides the power needed for the motor to function. The Arduino Uno acts as the interface between the driver and the rest of the system, sending the necessary commands to the driver to control the motor's movements. The following photo demonstrates how the driver has been used and connected to the stepper motor and Arduino.

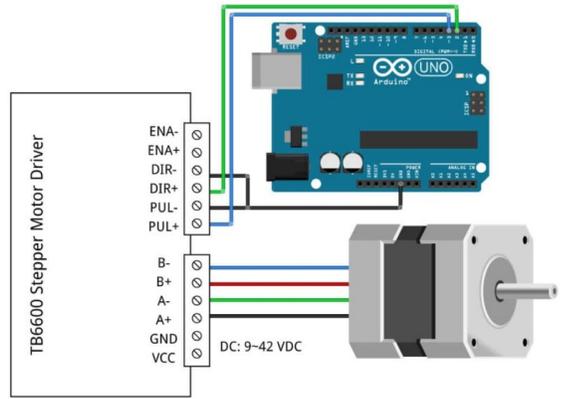


Figure 3-36 Connection of TB6600 to Arduino and stepper motor[50]

3.3.5.3 DC motor

In this research, a Direct Current (DC) motor was used for the membrane collector system. This type of motor converts direct current electrical energy into mechanical energy through the interaction between the magnetic field and electric current in the wire. The magnetic field is created by permanent magnets or electromagnets powered by DC voltage, and the electric current flowing through the motor's armature creates a rotational force, known as torque, which drives the motor shaft and produces mechanical work. DC motors are commonly used in a variety of applications, including household appliances, power tools, electric vehicles, and industrial automation systems. To operate, this motor requires a voltage of 5 volts and is connected to the output of the PLC Digital output. When activated by the robot, it will start rotating and collecting the membrane fibers.

3.3.5.4 Cutting system and Compaction system

It was mentioned earlier that both of these systems require pressurized air to function and that a solenoid actuator is used for this purpose. The solenoid actuator is connected to the Pneumatic systems electrical unit and receives an input voltage from the Digital Outputs of the PLC in order to control the flow of pressurized air to the various components in the system, such as the compaction and cutting systems.

The list of the components in the entire electrical system can be found in the following table.

Table 3-4 List of the components

System name	Actuator	Source of voltage	Require Voltage
Cutting system	Pneumatic solenoid	PSU 1 (12 volts)	12 v
Compaction	Pneumatic Solenoid	PSU 1 (12 volts)	12 v
Fan	Relay 1	PSU 1(12 volts)	12 v
Peltier	Relay 2	PSU 3 (5 volts)	5 v
Relay 1 and 2	PLC output DO [8]	PSU 3 (5 volts)	5 v
Collecting system	Servo motor	PSU 3 (5 volts)	5 v
Stepper motor	Stepper's driver	Stepper's driver	12 v
Stepper's Driver	-	PSU 2 (12 volts)	10.2 v
Arduino	-	PSU 3 (5 volts)	5 v
Robot PLC	-	PSU 3 (5 volts)	5 v

3.4 Summary

In this chapter the mechanical and electrical designs have been covered.

By identifying and considering all of the design constraints, subsystems has been designed and chosen, and due to the need of redesigning of some parts such as cutting system and guiding system, some improvements have been.

Next chapter focuses on determining the limitation of the AFP head based on its geometrical model. And in order to check the potential collisions simulations have been conducted and at the end the algorithms for fiber placement flat surface and V-shape structures have been developed.

Chapter 4

4 Geometric-based limitation Determination:

4.1 Introduction

In this chapter the focus is to determine the limitation of the AFP head when it is performing. Hence, the dimensions of the smallest corner that AFP can operate on the V-shaper part can be calculated. To this end, the simulation environments and methods have been used in order to validate the algorithms and find the smallest possible inner angle for V-shape structure.

4.2 Simulation

After finding the optimum values by trail and error in the CAD for the position and the distance between each component on the AFP Head, the head has been designed and implemented. Hence, the distances between each component could not get smaller, and accordingly, the AFP cannot get smaller than it is. Figure 4-1 shows the AFP design in the Solidworks software package, whereas Figure 4-2 represents the current AFP hardware design with the labeled components. Hence there are some limitations of the robot which have to be addressed and calculated. The first step is to simulate the process in a simulation environment in order to check the procedure of machining and the path planning.

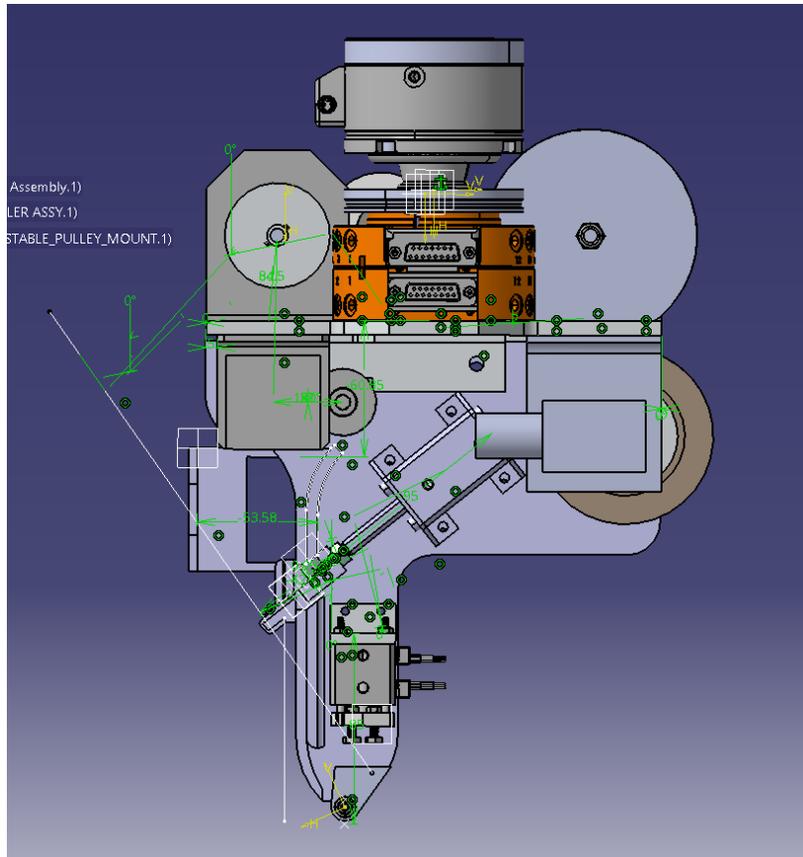


Figure 4-1 AFP head in Solidworks environment

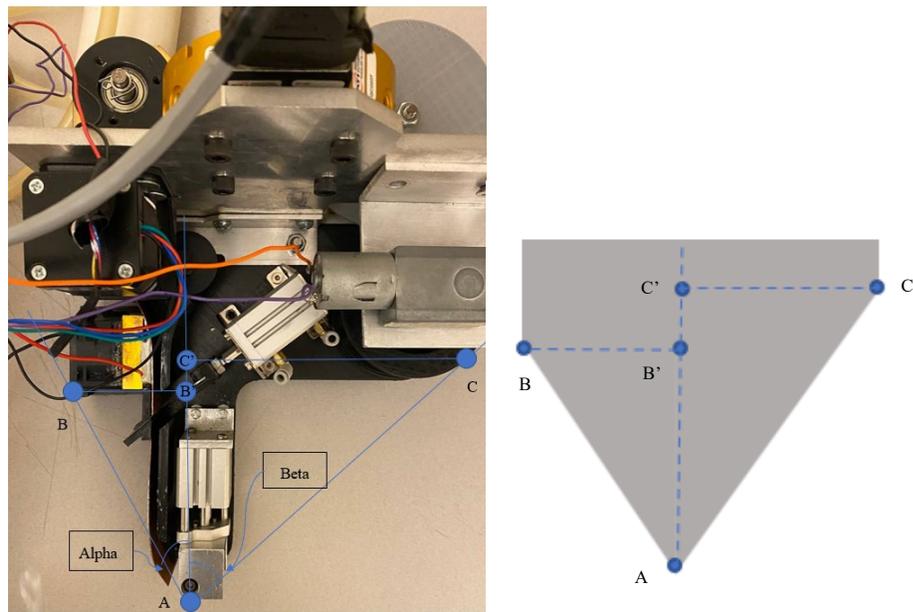


Figure 4-2 Schematics of the AFP based on the real design

4.2.1 RoboDK Simulation environment

In order to simulate the procedure of machining and generating the path, the RoboDK software package has been used. To do so, the floor, the table with the part attached to it, the Robot, the AFP head, and the parts which are going to be used as the mold are designed, imported, and assembled to each other in the RoboDK environment. Due to the compact design the AFP head is limited from the right side with the main spool (point C) and also from the left-hand side (point B) which is the fixture of the Fan.

4.2.2 Testing algorithm:

Using the RoboDK python programming, a code has been developed which aims to check the collision in the following steps:

1. The Robot, Floor, and Table are positioned to their home position.
2. The Testing part is placed on the table in its exact orientation and position (Using two holes in the table)
3. A Code start to be run which contains algorithms to extract all of the available lines on the parts at first and then delete the extra lines in order to reach the final path.
4. The Robot starts to move on the mentioned path after deriving all of the normal vectors of the part only one of the lines is selected which are the desired direction of depositing the layers.
5. The Robot also calculates the rotation under certain circumstances
6. Each time the robot is checking its collision with the surface on its path by moving on the path. If any collision is happening, it automatically breaks the code and restarts replacing the part with the next part. If not, it will follow the path to the end of it.
7. An Excel file is created accordingly and the final results are extracted which contains the values of the parameters and the result of the collision (yes if the collision happens no if not happened)

4.3 Testing Parts

4.3.1 Testing parts design

Each of the mold parts (testing part) consists of two plates which are connected together with a specific angle radius and length. After implementing the codes and a couple of tests, it has been discovered that the only parameters which can affect the machining paths and cause the collision are the parameters of the radius, angle, and length of the parts. These values have been mentioned in Figure 4-3.

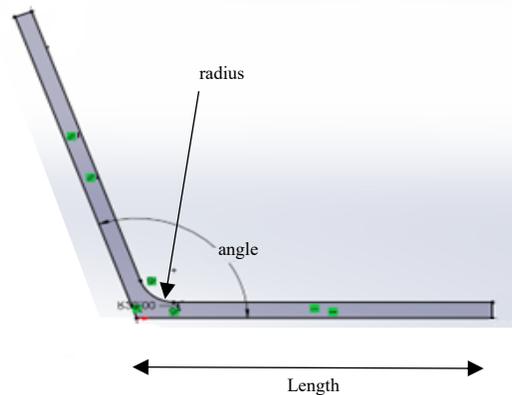


Figure 4-3 Critical parameters of the V-shape part

Hence, the objective is to find out which angle and radius are the smallest and at the same time is reachable for the Head in order to deposit the layer.

Due to the fact that there are two parameters that vary with specific spacing, there are a lot of designs which should be generated by Solidworks each time. The task is time-consuming and impossible. Hence a customized Plug-in was developed in order to facilitate this process.

4.3.2 Solidworks customized plugin method

The above-mentioned parts are being designed and generated by a plugin software in the Solidworks software package and the parameters are changing each time by the plugin which is developed specifically for this experiment.

We have developed this plugin using Macro programming by using the VBA language (Microsoft Visual Basic for Applications) which is embedded in the Solidworks software. The plugin also has a graphical user interface (GUI) as well.

The user should put their spaces and the limit of the length angle and the radius for the mold part. Hence the macro program will automatically generate each file and save it into a specific folder that is defined in the code. The code of this Plug in is available in **Appendix C**.

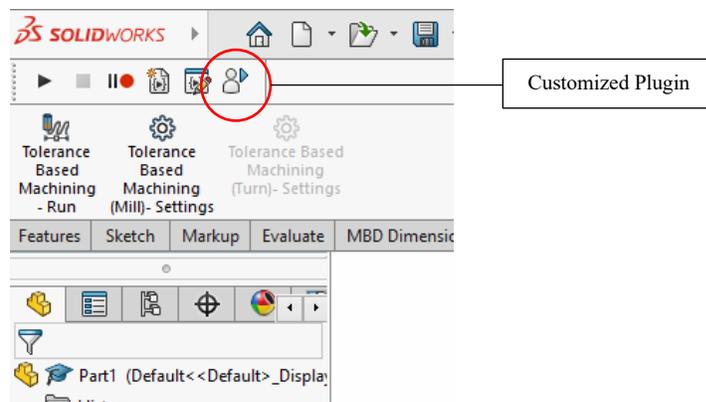


Figure 4-4 Solidworks Plugin

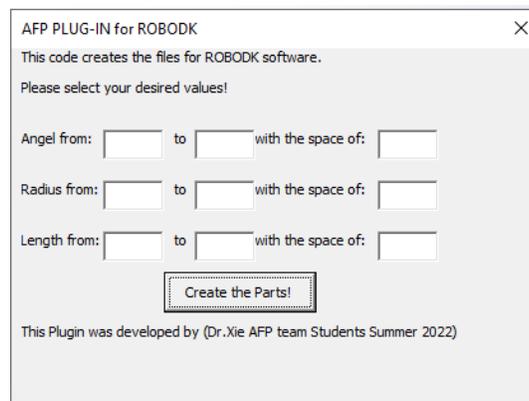


Figure 4-5 Plug-in GUI

Since this experiment has been conducted multiple times for the study parts consisting of two plates with a size of 200mm *200 mm, it has been identified that the size of the length of the mold will not affect the collision. Hence, there are only the angle and radius parameters which are getting changed for each CAD file.

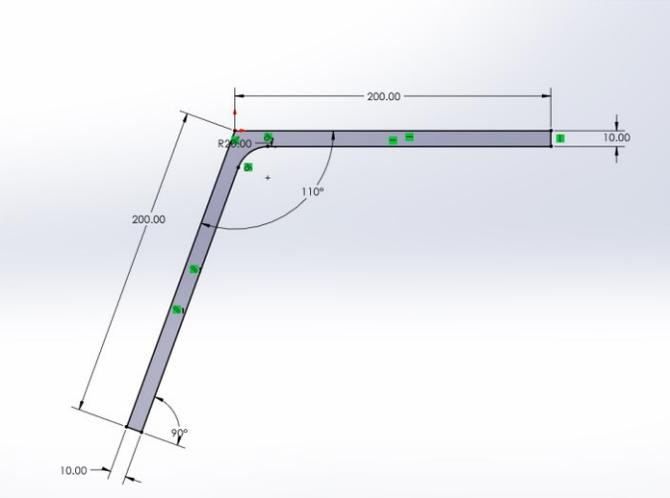


Figure 4-6 The sketch of the parts from the side view

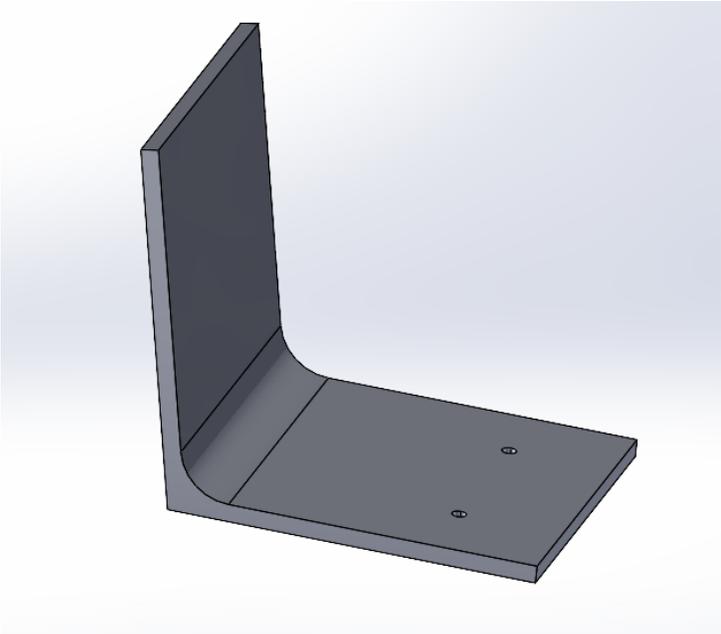


Figure 4-7 A testing part 3D CAD file

A path is also prepared as an output folder which saves all of the design parts in a folder with the STP extension format. Hence, the macro program will automatically generate each file and save it into a specific folder that is defined in the code.

4.4 Formulation

4.4.1 Limitations of final CAD design of AFP

As it is mentioned previously, the schematic of the AFP has been designed in order to derive the mathematical model from its geometry. Firstly, there is a chance of collision for point B on the left-hand side of the AFP which is shown in the following Figure when the AFP is moving on the surface of the V-shape part. There is also another limit on the left-hand side (point C) which is the backing spool. This limit is critical when there is a rotation due to the angle of the V-shape part. There is also an angle named as **AFP angle** i.e., the angle between the right-hand limit (point A-C line) and the left-hand limit on the fan fixture (point A-B line).

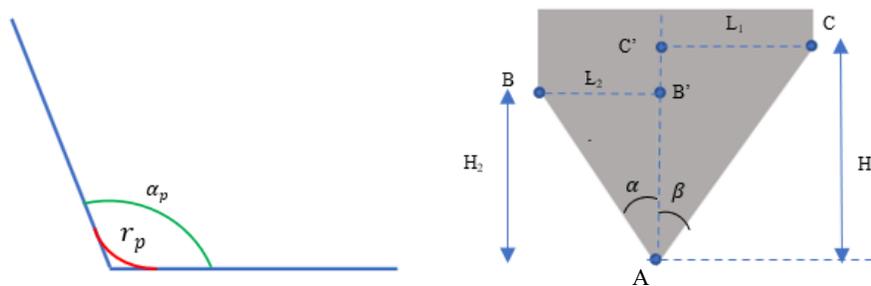


Figure 4-8 Simplified schematics of the part and AFP

The left picture is the part with an angle and a radius named as α_p and r_p respectively. On the right side of Figure 4-8, there is one point that is in the middle of the roller (point A), and there are two other points (point B and point C) which are showing the body and guide system (Fan) and collecting roller respectively. For each point, the distance from the roller has been defined as L_i , H_i and α and β are the radius of each line between the middle point of the roller and the points. Since

the part has a fillet with a specific radius, there is a curvature that will start at a certain point. The curvature starting point has been calculated as follows:

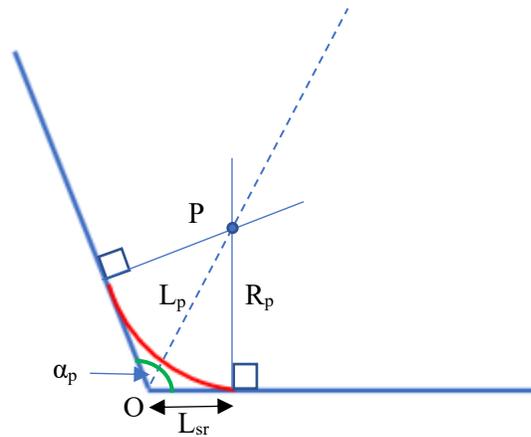


Figure 4-9 Part schematics with the radius included

$$\angle O = \frac{\alpha_p}{2} \quad (4.1)$$

$$L_p = \frac{R_p}{\sin\left(\frac{\alpha_p}{2}\right)} \quad (4.2)$$

$$L_{sr} = R_p \cdot \frac{\cos\left(\frac{\alpha_p}{2}\right)}{\sin\left(\frac{\alpha_p}{2}\right)} = R_p \cdot \cot\left(\frac{\alpha_p}{2}\right) \quad (4.3)$$

Normally the AFP head reaches the surface with a 90-degree angle (applying angle) (shown in Figure 4-10 by which the roller is normal to the surface). However, due to the design of the AFP following the path for doing fiber placement on V shape keeping the head normal to the surface is not feasible. Hence, there is a need for rotation at specific areas or points to avoid collision.

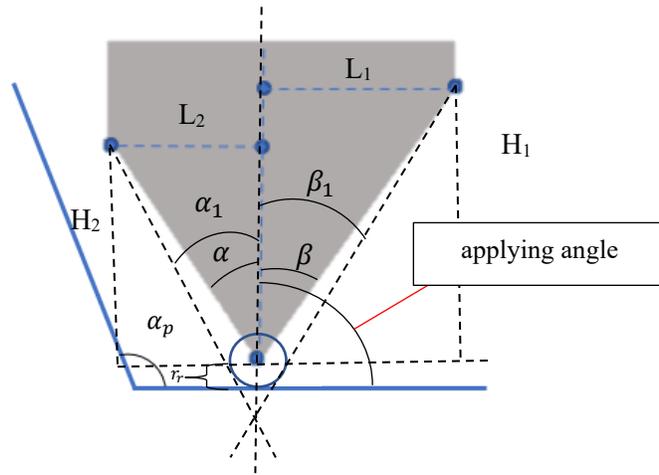


Figure 4-10 The AFP and the part side view with the roller

Table 4-1 Measured values from the Final project and CAD files

Parameters	Measured values
r_r	7.5 mm
α_1	48 degrees
β_1	47 degrees
α	34 degrees
β	50 degrees
L_1	165 mm
L_2	54 mm
H_1	116.7 mm
H_2	102.8 mm

Hence, before the collision happens there should be a rotation around the roller clockwise, and then after depositing the layers on the curved part of the V-shaped part, there is another clockwise rotation. It should be noted that the reason that α is smaller than α_1 is that in α_1 the guiding system and the screws have been considered and the limit is not only the Point B.

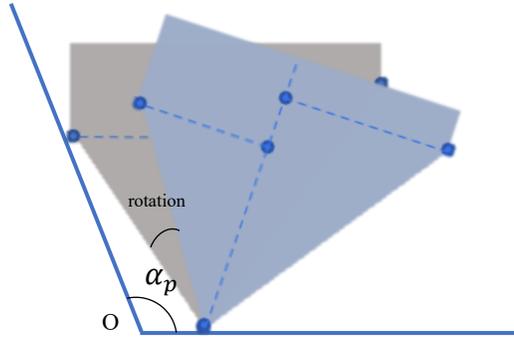


Figure 4-11 Schematics of the direction and position of the first rotation of AFP

In order to find the position of the point of the first rotation and the acceptable range of rotation angle, the following calculations have been carried out.

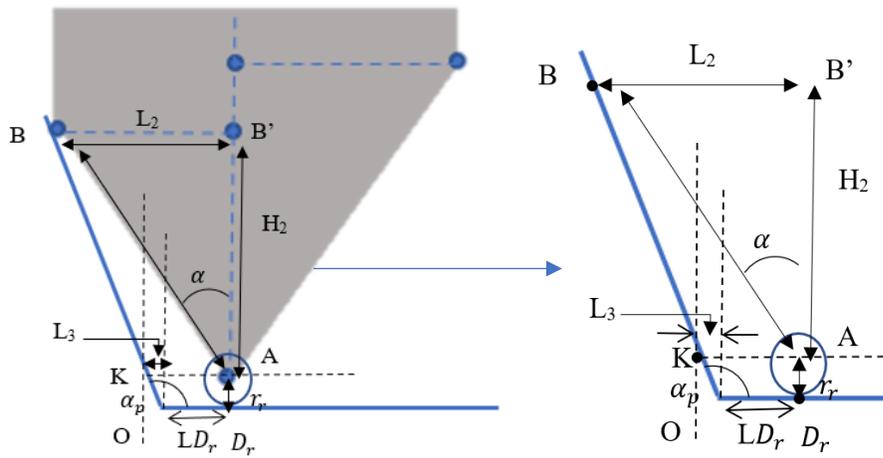


Figure 4-12 the first rotation point position

For the collision on the left side of the part, the AFP's head point that the collision happens has been named as D_r :

$$\tan\left(\alpha_p - \frac{\pi}{2}\right) = \frac{L_3}{r_r} \quad (4.4)$$

$$L_3 = r_r \cdot \tan\left(\alpha_p - \frac{\pi}{2}\right) \quad (4.5)$$

$$L_{D_r} + L_3 = L_4 \quad (4.6)$$

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

$$\frac{\sin\alpha_p}{\sqrt{(L_1^2 + h_1^2)}} = \frac{\sin\left(\frac{\pi}{2} + \alpha - \alpha_p\right)}{L_4} \quad (4.7)$$

$$\rightarrow L_4 = L_{D_r} + L_3 = \frac{\sin\left(\frac{\pi}{2} + \alpha - \alpha_p\right)}{\sin\alpha_p} \cdot \sqrt{(L_2^2 + H_2^2)} \quad (4.8)$$

$$L_{D_r} = L_4 - L_3 = \frac{\sin\left(\frac{\pi}{2} + \alpha - \alpha_p\right)}{\sin\alpha_p} \cdot \sqrt{(L_2^2 + H_2^2)} - r_r \cdot \tan\left(\alpha_p - \frac{\pi}{2}\right) \quad (4.9)$$

Hence L_{D_r} is the minimum distance of the first rotation point from the corner point (point O) of the part which means that the rotation should happen at a distance more than that otherwise the AFP will collide with the part.

There is a range of values for the first rotation angle (α_{r1}). The minimum and maximum values are as follows:

$$\min \alpha_{r1} = \left(\alpha_p - \alpha - \frac{\pi}{2}\right) \quad (4.10)$$

$$\max \alpha_{r1} = \left(\frac{\pi}{2} - \beta\right) + \sin^{-1}\left(\frac{r_r}{\sqrt{(L_1^2 + H_1^2)}}\right) \quad (4.11)$$

$$\rightarrow \left(\alpha_p - \alpha - \frac{\pi}{2}\right) \leq \alpha_{r1} \leq \left(\frac{\pi}{2} - \beta\right) + \sin^{-1}\left(\frac{r_r}{\sqrt{(L_1^2 + H_1^2)}}\right) \quad (4.12)$$

Hence, the collision points and allowed rotation range are found.

4.4.2 Rotations and positions

In the following, the positions of the rotations have been described.

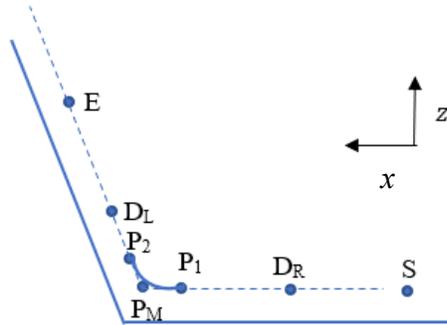


Figure 4-14 Rotation positions

As mentioned in Figure 4-14 Point S represents the starting point, and Point D_R represents the first rotation point after this point the head will continue its path till point P_1 and then there is a circular movement from that point P_1 to point P_2 with using P_m as the middle point.

After that, the robot will move to the D_L point, and then another clockwise rotation happens at that point. Then there is a linear movement till the end of the path which is point E.

It should be noted that the other point like the cutting point and compaction system actuation point will be discussed in depth at the end of this chapter.

The robot starts at its starting position which is point S. Then the robot follows its path to the first rotation point which is D_r and rotates of α_{r1} .

$$\text{Position of Point } S = \begin{bmatrix} 0 \\ 0 \\ r_r \end{bmatrix} \quad (4.17)$$

$$\text{Position of Point } D_r = \begin{bmatrix} l_p - l_{Dr} \\ 0 \\ r_r \end{bmatrix} \quad (4.18)$$

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

$$R_{r1} = \begin{bmatrix} \cos \alpha_{r1} & 0 & \sin \alpha_{r1} \\ 0 & 1 & 0 \\ -\sin \alpha_{r1} & 0 & \cos \alpha_{r1} \end{bmatrix} \quad (4.19)$$

Then the robot will move to the next point which is point P_1 and will do a circular movement from P_1 to P_2 with the middle point of P_M . Then the robot will reach the point D_l which is the second rotation point and will rotate with α_{r2} angles. In the end, the robot will follow its path till the Endpoint which is point E .

$$\text{Position of Point } P_1 = \begin{bmatrix} l_p - l_{sr} \\ 0 \\ r_r \sin(90 - \alpha_r) \end{bmatrix} \quad (4.20)$$

$$\text{Position of Point } P_M = \begin{bmatrix} l_p - \left(\frac{r_p}{\cos(\frac{\alpha_p}{2})} - r_p \right) \cdot \cos\left(\frac{\alpha_p}{2}\right) \\ 0 \\ \left(\frac{r_p}{\cos(\frac{\alpha_p}{2})} - r_p \right) \cdot \sin\left(\frac{\alpha_p}{2}\right) \end{bmatrix} \quad (4.21)$$

$$\text{Position of Point } P_2 = \begin{bmatrix} l_p + (l_{sr} \cos(180 - \alpha_p)) \\ 0 \\ (l_{sr} \sin(180 - \alpha_p)) + r_r \sin(\alpha_p - 90 - \alpha_r) \end{bmatrix} \quad (4.22)$$

Position of Point $D_l =$

$$\begin{bmatrix} l_p + (l_{Dl} \cos(180 - \alpha_p)) - r_r \cos(\alpha_p - 90 - \alpha_r + \alpha_l) \\ 0 \\ (l_{Dl} \sin(180 - \alpha_p)) + r_r \sin(\alpha_p - 90 - \alpha_r) \end{bmatrix} \quad (4.23)$$

Second rotation matrix with the rotation of $\alpha_{r2} =$

$$R_{r2} = \begin{bmatrix} \cos \alpha_{r2} & 0 & \sin \alpha_{r2} \\ 0 & 1 & 0 \\ -\sin \alpha_{r2} & 0 & \cos \alpha_{r2} \end{bmatrix} \quad (4.24)$$

Position of Point $E =$

$$\begin{bmatrix} l_p + (l_p \cos(180 - \alpha_p)) - r_r \cos(\alpha_p - 90 - \alpha_r + \alpha_l) \\ 0 \\ (l_p \sin(180 - \alpha_p)) + r_r \sin(\alpha_p - 90 - \alpha_r + \alpha_l) \end{bmatrix} \quad (4.25)$$

where α_{r1} and α_{r2} are the rotation angles, l_p is the length of the part, l_{Dr} and l_{Dl} are the length of the rotation point from the middle point of the part and l_{sr} is the length of the filet section on the part.

4.5 Simulation using RoboDK and the algorithms for the rotation

4.5.1 Determining the Normal and non-normal mode

As it has been mentioned earlier, there are two modes in order to deposit the layers in the simulation.

- **Normal mode:**

Based on the CAD file and simulation, this mode is only functional for angles more than 138 degrees ($\frac{\pi}{2} + \text{Alpha}$) by which the collision is prevented. In this mode, there is no need for the robot to do any additional rotations before the robot reaches the middle of the part.

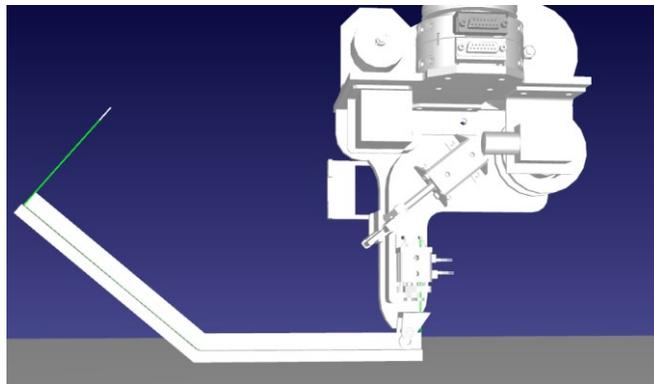


Figure 4-15 138 degrees and more angle for the part

- **Non-Normal mode:**

This mode is only functional for the angles less than 138 degrees by which the collision is prevented. And the robot should rotate by the calculated values.

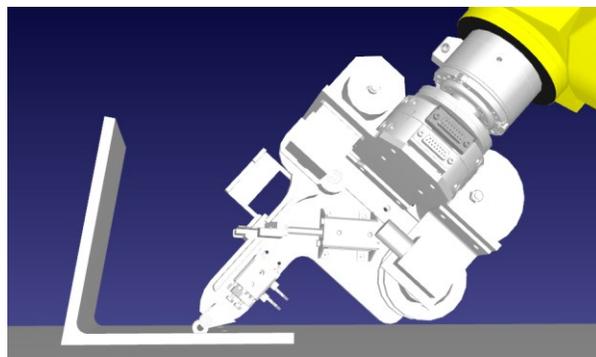


Figure 4-16 138 degrees and less angles for the part

20mm, 30 mm, 40 mm, 50 mm, and 60 mm. Additionally, the video of the following steps and simulation is available through this [link](#). The code of the simulation is available in **Appendix D**.

4.5.2.1 Final results by changing one parameter at the time

In order to find out which values are acceptable for the parameters, each of them has been checked individually. Hence, one of the parameters is fixed and the other one is changing at the time. It should be noted that the length is not known as a variable since it is not influencing the final value. Hence, by default, it has been considered as a fixed value. In order to simplify the report and reduce extra values, we have provided the critical values in the critical ranges for both parameters.

The table below only gives the critical values, and the full values are also mentioned in the next tables. It is obvious that from a point the AFP will always collide with the part in all of the angles below a specific value (despite changing the other parameter) and also it will not collide above a certain point (despite changing the other parameter).

Table 4-2 Fixed angle (91 degrees)

Radius	10mm	20mm	30mm	40mm	50mm	60mm
Collision	Yes	Yes	No	No	No	No

Table 4-3 Fixed angle (92 degrees)

Radius	10mm	20mm	30mm	40mm	50mm	60mm
Collision	Yes	Yes	No	No	No	No

Table 4-4 Fixed angle (93 degrees)

Radius	10mm	20mm	30mm	40mm	50mm	60mm
Collision	Yes	Yes	No	No	No	No

Table 4-5 Fixed angle (94 degrees)

Radius	10mm	20mm	30mm	40mm	50mm	60mm
Collision	Yes	No	No	No	No	No

Table 4-6 Fixed angle (95 degrees)

Radius	10mm	20mm	30mm	40mm	50mm	60mm
Collision	Yes	No	No	No	No	No

Table 4-7 Fixed angle (96 degrees)

Radius	10mm	20mm	30mm	40mm	50mm	60mm
Collision	No	No	No	No	No	No

Table 4-8 Fixed angle (97 degrees)

Radius	10mm	20mm	30mm	40mm	50mm	60mm
Collision	No	No	No	No	No	No

Table 4-9 Fixed radius (10 mm)

angle	91 degrees	92 degrees	93 degrees	94 degrees	95 degrees	96 degrees	97 degrees
Collision	Yes	Yes	Yes	Yes	Yes	No	No

Table 4-10 Fixed radius (20 mm)

angle	91 degrees	92 degrees	93 degrees	94 degrees	95 degrees	96 degrees	97 degrees
Collision	Yes	Yes	Yes	Yes	Yes	No	No

Table 4-11 Fixed radius (30 mm)

angle	91 degrees	92 degrees	93 degrees	94 degrees	95 degrees	96 degrees	97 degrees
Collision	No						

Table 4-12 Fixed radius (40 mm)

angle	91 degrees	92 degrees	93 degrees	94 degrees	95 degrees	96 degrees	97 degrees
Collision	No						

Table 4-13 Fixed radius (50 mm)

angle	91 degrees	92 degrees	93 degrees	94 degrees	95 degrees	96 degrees	97 degrees
Collision	No						

Table 4-14 Fixed radius (60 mm)

angle	91 degrees	92 degrees	93 degrees	94 degrees	95 degrees	96 degrees	97 degrees
Collision	No						

4.5.2.2 Final result by changing all of the parameters at the same time

Table 4-15 Final results by changing all of the parameters

Collisions (Yes or No)	Angle (Degrees)	91	92	93	94	95	96	97	98	99	100	101	102
Radius(mm)													
10		Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No
20		Yes	Yes	Yes	No	No	No	No	No	No	No	No	No
30		No	No	No	No	No	No	No	No	No	No	No	No
40		No	No	No	No	No	No	No	No	No	No	No	No
50		No	No	No	No	No	No	No	No	No	No	No	No
60		No	No	No	No	No	No	No	No	No	No	No	No

4.5.3 Modification of simulations

As it has been mentioned earlier, AFP angle is the only and the most important parameter from the AFP side. The main objective is to reach the smallest angle of a fiber placement part. It is desired to have the smallest AFP angle possible, which is only possible in three ways:

1. Decreasing the space between components; hence the total width gets smaller which has been shown in Figure 4-18.

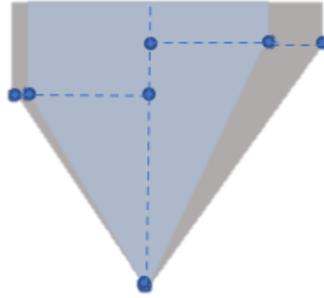


Figure 4-18 The modification of the width

2. Increasing the length of the roller and fan (increase the H length to have H' as mentioned in Figure 4-19. If H of AFP is increased, α and β will be smaller and there will be a lower chance of collision)

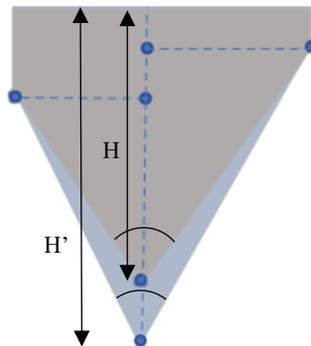


Figure 4-19 The modifications on the length

3. Increasing the size of the roller and deleting and replacing the screws on the guiding system with headless screws.

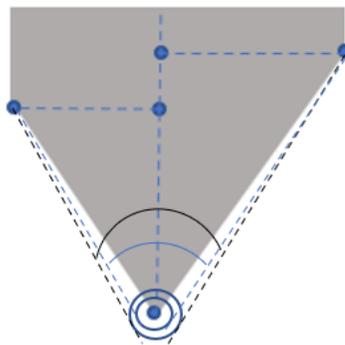


Figure 4-20 The modification in the size of the roller

The first and second aforementioned ways are not feasible due to the following reasons:

- For the first one, as it has been described earlier, the current design is the most possible compact design based on the available components with the minimum distance of them.
- The second one will not work as well due to the fact that by increasing the length it is more possible for the layers to stick to the guiding system. Hence it is necessary to implement and add another fan in between which makes the AFP angle again a large value.

But the third one is easy to modify on the simulation and CAD to check the effect on the final part angle. Hence, the roller size has been changed to 10 mm instead of 7.5 mm and the previous steps and parts have been tested on it, also the screw has been changed to headless screws. Since the smallest possible corner for the AFP to deposit a fiber prepreg is the same size as the roller, increasing the radius of the roller means that the robot will not be capable of doing this procedure for parts with radii smaller than its new radius

4.5.3.1 Final results by changing one parameter at the time

In order to determine the acceptable values for each parameter, each parameter was checked individually while keeping one fixed and changing the other. It should be noted that the length was considered a fixed value since it did not influence the final value. For the sake of simplicity and reduced information, only the critical values within the critical ranges for both parameters were provided in the table below. The full values for each parameter were included in the subsequent tables. It is important to note that for all angles below a certain value, the AFP will collide with the part, irrespective of changes to the other parameter. Similarly, no collision will occur above a certain point, irrespective of the value of the other parameter. These changes show that by increasing the size of the roller and deleting the head of the screws on the guiding system, the minimum feasible angle could get smaller to 80 degrees.

Table 4-16 Fixed angle (78 degrees)

Radius	10mm	20mm	30mm	40mm	50mm	60mm
Collision	Yes	Yes	Yes	Yes	Yes	Yes

Table 4-17 Fixed angle (79 degrees)

Radius	10mm	20mm	30mm	40mm	50mm	60mm
Collision	Yes	Yes	Yes	No	No	No

Table 4-18 Fixed angle (80 degrees)

Radius	10mm	20mm	30mm	40mm	50mm	60mm
Collision	No	No	No	No	No	No

Table 4-19 Fixed angle (81 degrees)

Radius	10mm	20mm	30mm	40mm	50mm	60mm
Collision	No	No	No	No	No	No

Table 4-20 Fixed radius (10 mm)

angle	77 degrees	78 degrees	79 degrees	80 degrees	81 degrees	82 degrees
Collision	Yes	Yes	Yes	No	No	No

Table 4-21 Fixed radius (20 mm)

angle	77 degrees	78 degrees	79 degrees	80 degrees	81 degrees	82 degrees
Collision	Yes	Yes	Yes	No	No	No

Table 4-22 Fixed radius (30 mm)

angle	77 degrees	78 degrees	79 degrees	80 degrees	81 degrees	82 degrees
Collision	Yes	Yes	Yes	No	No	No

Table 4-23 Fixed radius (40 mm)

angle	77 degrees	78 degrees	79 degrees	80 degrees	81 degrees	82 degrees
Collision	Yes	Yes	No	No	No	No

Table 4-24 Fixed radius (50 mm)

angle	77 degrees	78 degrees	79 degrees	80 degrees	81 degrees	82 degrees
Collision	Yes	Yes	No	No	No	No

Table 4-25 Fixed radius (60 mm)

angle	77 degrees	78 degrees	79 degrees	80 degrees	81 degrees	82 degrees
Collision	Yes	Yes	No	No	No	No

4.5.3.2 Final result by changing all of the parameters at the same time:

Table 4-26 Final results by changing all of the parameters

Collisions (Yes or No)	Angle (Degrees)	74	75	76	77	78	79	80	81	82	83	84	85
Radius(mm)													
10		Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No
20		Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No
30		Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No
40		Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No
50		Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No
60		Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No

4.6 Robot offline programming and path planning

As it has been mentioned earlier, Robot Offline Programming (OLP) is the process of programming a robot using simulation and offline software, instead of directly controlling the robot on the shop floor. With OLP, the robot's path and motion can be planned, programmed, and tested in a virtual environment before being implemented in a real-world application. The goal of OLP is to increase the efficiency and safety of robot programming, reduce the time required for programming, and improve the quality and consistency of the result. OLP allows the user to validate the robot program in a safe and controlled environment, which reduces the risk of

equipment damage or operator injury. In short, OLP provides a convenient and cost-effective method for robot programming and deployment.

Whereas Robot online programming refers to the process of controlling and programming a robot while it is running and performing tasks. In online programming, the robot's motion and actions can be programmed, modified, or reprogrammed while it is in operation, without having to stop or shut down the system. This allows for real-time adjustments and quick changes to the robot's program, making it possible to respond to changing conditions on the production line or in the work environment. Online programming is commonly used in industrial automation and allows for greater flexibility, efficiency, and productivity in the manufacturing process.

In light of the limitations and restrictions posed by having a closed-loop control system for the robot, an offline programming path planning process was utilized for this project. This method was employed to create software for depositing layers on a surface and also for depositing layers on the inner surface of V-shaped structures.

4.6.1 Software development for depositing the layers on a surface

In order to deposit the layers of composite on a surface, a specific software was required. This software was developed for generating the code for the robot to deposit the layers of composite on a surface which is an important component of the overall system. This software makes it easier for the operator to specify the various parameters and features for the depositing process such as speed, name, length, width, gap size, and performance mode. With this software, the operator does not need to manually write the code from scratch, but can simply input the desired values and generate the final code using the Python and RoboDK libraries.

Once the code is generated, it can be translated from Python language to Korel language which is the language that the Fanuc robot can understand. This ensures that the robot is able to accurately follow the instructions given in the code. The code can then be displayed on the teach pendant and the operator can manually run it using the pendant.

The robot will then follow each line of the program one by one, performing the depositing process according to the specifications set in the code. When the program is complete, the robot will notify the operator through the teach pendant screen. Overall, this software makes the depositing process more efficient, streamlined, and customizable for the operator.

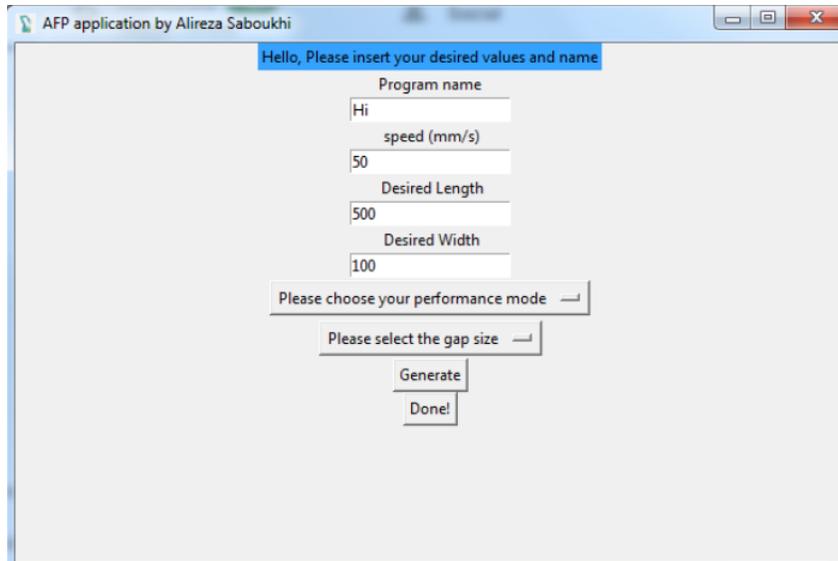


Figure 4-21 GUI of the software for depositing the layers on a surface

The predefined values help make the process of choosing the values easier for the operator, but the operator has the option to change them if needed. For instance, the user has the option to change between Normal, fast Mode, and Test mode. The Test mode refers to a single cycle, while the Normal and Fast modes refer to multiple cycles with differences in Y direction and procedure. These differences will be further explained in the algorithm section.

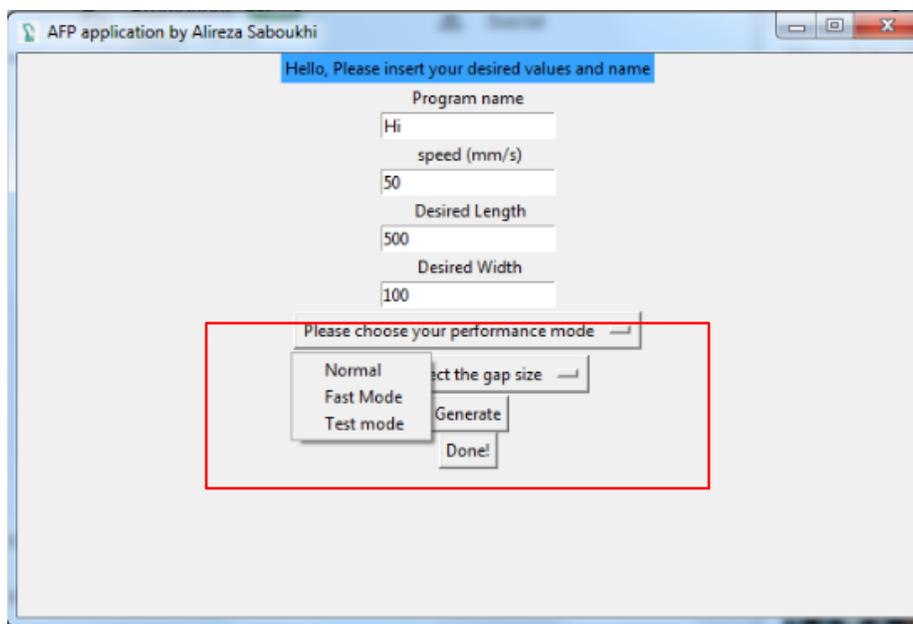


Figure 4-22 Performance mode section

In the software, the user has the option to select the gap size, which determines the offset between each layer of composite material. This value can be set by the user, but it can also be predefined to facilitate the process. The gap size is used in the path planning algorithm to determine the position of each layer. In the Fast or Normal mode, the Y direction of each subsequent layer is increased by the width of the tow plus the gap size. This allows the operator to control the thickness of the composite material and produce a final product with the desired properties.

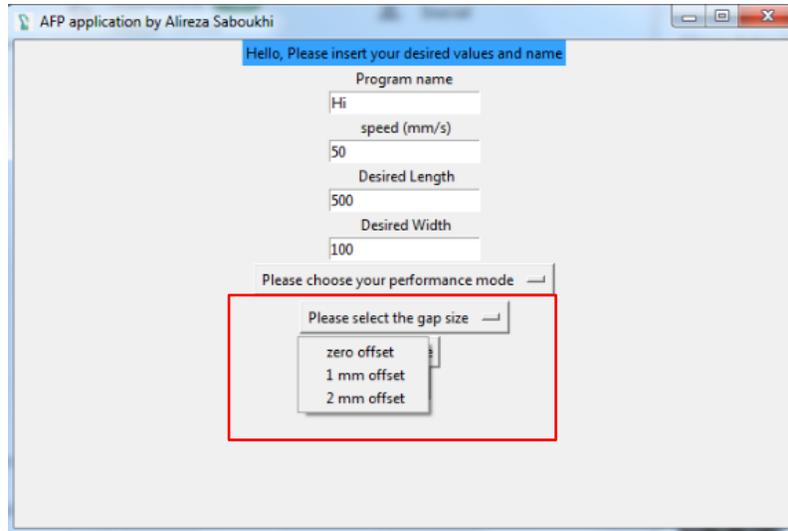


Figure 4-23 Gap size section

4.6.1.1 Algorithm of the software:

For each iteration, the code will first check the mode selected by the user (Normal, Fast, or Test). Based on the selected mode, the code will calculate the position of the next layer to be deposited. In the Test mode, the code will only deposit one layer, and the algorithm won't repeat. whereas for the other modes, the algorithm will be repeated N times which is the round value of the division of the desired width(W) over the width of tow or (T).

$$n = W/T \quad (4.27)$$

For example, if the user selected the Normal mode, the code will deposit the first layer with a certain gap size and then move to the next layer by incrementing the position in the Y direction by the sum of the width of the tow (T) and the gap size (G). This process will be repeated until all the

layers have been deposited, and the final width of the deposited composite is equal to the desired width (W).

Finally, the code will generate the path planning code in the Korel language, which can be run on the robot with the Teach Pendant. The robot will follow each line of the program and deposit the layers according to the algorithm until the process is complete. The code of the algorithm is available in **Appendix E**.

The following passage describes a six-step algorithm for robot offline programming in the context of depositing layers of material on a surface.

First step: In order to avoid any collision, first of all the AFP head will be first positioned at a specific location above the starting point. This means that due to the fact that the Y direction is kept fixed the X and Z positions are larger than the starting point's X_0 and Z_0 . This position is referred to as the insurance position: (X_i, Y_0, Z_i) .

AFP position: (X_i, Y_0, Z_i)

Second step: The AFP head will be moved to a position with a small distance before the starting point in the X direction, with the height (Z) being exactly the value of the compaction system range (Z_0). The feeding system (stepper motor) will be turned on, bringing the tow below the compaction roller and the collector roller (DC motor) will start collecting the membranes of the tow.

These motors are receiving the command from the code which is actuating the PLC of the Fanuc controller.

AFP position: $(X_0 - X_e, Y_0, Z_0)$

Third step: the robot starts to move on the surface at the predefined speed. Once it reaches the X_0 position, the compaction roller will be activated by the PLC and its pneumatic system. Hence it will apply the desired force to the tow to stick it to the surface.

AFP position: (X_0, Y_0, Z_0)

Forth step: Once the robot reaches the cutting position (X_c). The cutting system will be activated by the PLC and its pneumatic system for 0.5 seconds which leads to cutting the tape.

AFP position: (X_c, Y_0, Z_0)

Fifth step: Due to the fact that the cutting function has been done at a specific point inside the AFP head, there is a need to move further to deposit all of the tapes. Hence the Robot will reach to (X_f) position which is the final position for the AFP for each course. This value is $X_c+120\text{mm}$.

AFP position: (X_f, Y_0, Z_0)

Sixth step: The aforementioned steps describe the procedure for the test mode. At the end of the test mode, the robot returns to its initial position (first step).

Test Mode AFP position: (X_i, Y_0, Z_i)

If the mode is defined as Normal, the procedure will be repeated for each subsequent cycle and as mentioned before, the Y direction will be increased by $T+G$ which is the width of the tow and the Gap respectively.

Normal Mode AFP position: (X_i, Y_0+T+G, Z_i)

And if the user chooses to have the path planning in the fast mode version. This means that the robot will rotate 180 degrees at the endpoint. And the next cycle will start at the end position and the robot move from right to left. And this happens again for the next steps as well.

It should also be noted that after finishing the first course, the robot will increase its Height and then do the rotation. It should also go in and move further to the right-hand side like the second step.

Fast Mode AFP position: (X_f+X_c, Y_0+T+G, Z_i)

Figures 4-24 present the generated code on the computer (left picture) and the code which is sent to the robot and is shown on the Teach pendant (right picture).

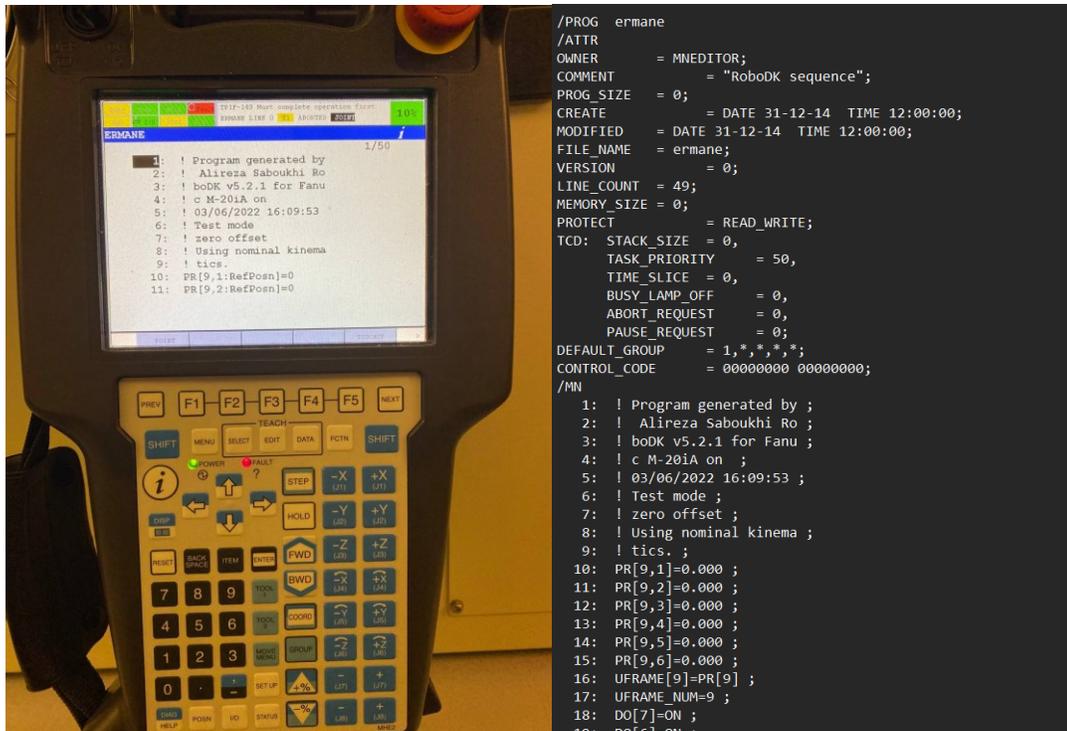


Figure 4-24 The generated code on the PC in the LS format and in Teach Pendant

4.6.2 Software development to deposit the layers on the inner surface of V-shape sample parts

In order to deposit the layers of composite on the inner surface of the V-shaped parts, a specific software was required.

Like the previous software, this software was developed for generating the code for the robot to deposit the layers of composite on a surface of a part which in this case is a V-shaped part. This means that this software should have different orientations for the AFP head. The operator should specify various parameters and features for the depositing process such as the angle of the corner, the radius of the corner, speed, name, length, and width. The software has enabled operators to streamline the path-planning process for robotic systems. Rather than requiring the operator to manually write code to control the robot, the software allows for easy input of the desired values. The Python and RoboDK libraries are used to generate the final code, which can then be implemented to control the robotic system.

The benefits of this approach listed as follows. By eliminating the need for manual coding, the operator can save a significant amount of time and reduce the risk of errors. Additionally, the use of Python and RoboDK libraries ensures that the generated code is highly efficient and accurate, further enhancing the performance of the robotic system. Figure 4-25 represents the GUI for the computer software for Fiber placement V-shape structures.

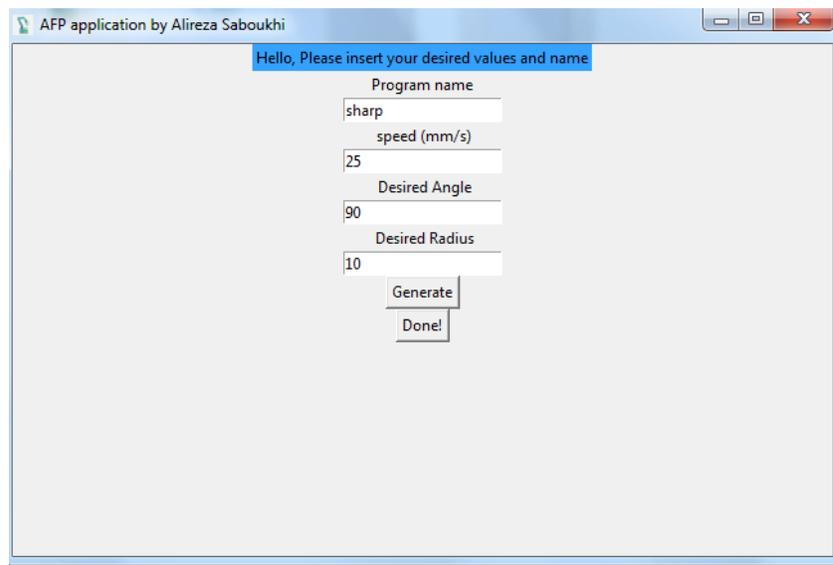


Figure 4-25 GUI of the software for depositing the layers on a V-shaped structure

The software has been designed to be highly flexible, allowing for customization to meet the needs of specific applications. This ensures that the system can be easily adapted to a wide range of use cases, providing a powerful tool for the development of robotic systems in many industries.

The software allows for the automatic generation of code using Python and RoboDK libraries. The generated code is translated into Korel language to ensure accurate execution by the Fanuc robot. The teach pendant is used to manually run the program, and the robot performs the depositing process according to the specifications set in the code. The software improves efficiency and provides greater flexibility for the operator. The robot notifies the operator when program execution is complete.

The current code has been designed to run only one cycle and the robot will not automatically move on to the next cycle after the deposition is complete. This design is intentional and has been implemented due to the nature of the objective and tests being conducted. By running a single cycle, the operator can better monitor the deposition process and ensure that it meets the desired

specifications. Additionally, this approach allows for more precise control over the deposition process and reduces the risk of errors or defects in the final product. The code of the algorithm is available in **Appendix F**.

An additional noteworthy aspect of this code is that orientation changes must be made with respect to the midpoint of the roller. To account for this, the offset between the midpoint of the roller and the midpoint of the tool changer has been established as the tool position within the code. This ensures that the robot properly orients itself during the deposition process, resulting in accurate and precise deposition of the material.

4.6.2.1 Algorithm of the software:

This section depends on the V-shape angle value. If the angle is less than 138 degrees it will be a twelve-step algorithm and if it is more than that it will be a ten-step algorithm. It is worth noting that an additional rotation was incorporated into the algorithms during the simulation and experimental tests to avoid losing pressure on the tapes due to excessive movement.

The following passage describes a twelve-step algorithm for robot offline programming for fiber placement on the tight corners of the V-shape structure with a value of fewer than 138 degrees.

First step: Like the previous code in order to avoid any collision, the AFP head will be positioned at a specific location above the starting point. The X direction is kept fixed when the Y and Z positions are larger than the starting point's Y_0 and Z_0 . This position is referred to as the insurance position: (X_0, Y_i, Z_i) .

AFP position: (X_0, Y_i, Z_i)

Second step: The AFP head will be moved to a position with a small distance before the starting point in the Y direction, with the height (Z) being exactly the value of the compaction system range (Z_0). The feeding system (stepper motor) will be turned on, bringing the tow below the compaction roller and the collector roller (DC motor) will start collecting the membranes of the tow.

These motors are receiving the command from the code which is actuating the PLC of the Fanuc controller.

AFP position: $(X_0, Y_0 - Y_e, Z_0)$

Third step: The robot begins moving linearly on the surface at a predefined speed and activates the compaction roller, which applies force to stick the tow to the surface when it reaches the starting point (X_0, Y_0, Z_0) .

AFP position: (X_0, Y_0, Z_0)

Forth step: Once the robot reaches the First rotation position (Y_1) , the robot should move $\alpha_{r1} - x$ degree around the Y axis in order to prevent the collision from the left-hand side of the Robot. The aforementioned values should be defined based on the radius and angle of the part. The amount of the x has been founded by trial and error in the experimental tests and it was equal to 5 degrees.

AFP position: (X_0, Y_1, Z_0)

Fifth step: The Robot continues its path linearly till it reaches Y_{P1} which is the first point of the filet of the Part and that is the last linear movement on the bottom plate.

AFP position: (X_0, Y_{P1}, Z_0)

Sixth step: The Robot starts a circular movement from Y_{P1} to the middle point of the filet Y_m . The orientation is unchanged. In order to reach that point, the roller should be raised so there is an increase in the Z axis as well.

AFP position: (X_0, Y_m, Z_m)

Seventh step: The Robot rotates when it is in this point with x degree around the Y axis in order to complete the α_{r1} complete rotation. This rotation is in the same orientation as the previous rotation because of the proposed Robot specification.

AFP position: (X_0, Y_m, Z_m)

Eighth step: The robot continued the circular movement with the new orientation till the end of the filet of the part (Y_{P2}) .

AFP position: (X_0, Y_{P2}, Z_{P2})

Ninth step: The robot continued its path linearly from Y_{P2} to the second rotation position Y_2 and then it rotates α_{r2} degrees around the Y axis.

AFP position: (X_0, Y_2, Z_2)

Tenth step: The robot continues the path till it reaches the cutting point Y_c . In this position, the PLC will activate the cutter to cut the tape.

AFP position: (X_0, Y_c, Z_c)

Eleventh step: The robot continues the path till it reached the endpoint (Y_e) in which the compaction system gets off by the PLC.

AFP position: (X_0, Y_e, Z_e)

Twelfth Step: the robot will go back to the initial position in the first step and gets ready for the next test.

AFP position: (X_0, Y_i, Z_i)

The following sections describes a ten-step algorithm for robot offline programming for fiber placement on the tight corners of the V-shape structure with a value of more than 138 degrees.

First step: Similar to the previous code, the AFP head will be initially positioned above the starting point to prevent any collision. This implies that while the X direction is kept fixed, the Y and Z positions of the AFP head will be greater than the corresponding Y_0 and Z_0 positions of the starting point. This position is referred to as the insurance position: (X_0, Y_i, Z_i) .

AFP position: (X_0, Y_i, Z_i)

Second step: To initiate the fiber placement process, the AFP head will be moved a short distance in the Y direction to a position just before the starting point. The height (Z) of the AFP head will be set precisely to the compaction system range value (Z_0).

Once in position, the feeding system (stepper motor) will be activated, causing the tow to be passed below the compaction roller. At the same time, the collector roller (DC motor) will start collecting the tow membranes.

Both the feeding and collector motors will be controlled by the code, which will actuate the PLC of the Fanuc controller. This will ensure accurate and precise control of the motors, resulting in a successful fiber placement process.

AFP position: (X_0, Y_0-Y_e, Z_0)

Third step: At the starting point (X_0, Y_0, Z_0) , the robot will begin to move linearly across the surface at a predetermined speed. As it moves, the compaction roller will be activated, exerting a force that will bond the tow to the surface.

AFP position: (X_0, Y_0, Z_0)

Forth step: The Robot continues its path linearly till it reaches Y_{P1} which is the first point of the filet of the Part and that is the last linear movement on the bottom plate.

AFP position: (X_0, Y_{P1}, Z_0)

Fifth step: The Robot starts a circular movement from Y_{P1} to the middle point of the filet Y_m . The orientation is unchanged. In order to reach that point, the roller should be raised so there is an increase in the Z axis as well.

AFP position: (X_0, Y_m, Z_m)

Sixth step: the Robot rotates when it is at this point with $\pi - \alpha_{rp}$ degree around the Y axis to be perpendicular to the surface.

AFP position: (X_0, Y_m, Z_m)

Seventh step: The robot continues the circular movement with the new orientation till the end of the filet of the part (Y_{P2}).

AFP position: (X_0, Y_{R2}, Z_{P2})

Eighth step: The Robot continues its path linearly from Y_{P2} till it reaches the cutting point Y_c . In this position, the PLC will activate the cutter to cut the tape.

AFP position: (X_0, Y_c, Z_c)

Ninth step: The robot continues the path till it reached the endpoint (Y_e) in which the compaction system gets off by the PLC.

AFP position: (X_0, Y_e, Z_c)

Tenth step: The robot will go back to the initial position in the first step and gets ready for the next test.

4.7 Summary

In this chapter, detailed analysis has been carried out based on the geometrical model in order to calculate the limitations. Using the limitations, the positions and values of rotations have been calculated and used in order to check the smallest possible angle and radius.

After successful tests on the RoboDK simulation environment, some modification has been done only on the CAD file of the AFP head to check the capability of reaching a smaller radius and angle. This modifications shows that by changing the size of the roller and using headless screws smaller angles are reachable.

The next step involves implementing and building the test setup with the same angle and radius to validate the simulation result in experimental test. This will be addressed in the upcoming chapter.

Chapter 5

5 Verification and Experiment results:

5.1 Introduction

The purpose of the proposed AFP head is to be able to deposit the fiber layers in tight angles of complex parts. After doing some tests based on the simulation environment, the minimum value of the parameters of the part should be verified.

In this chapter, the experimental setup of the AFP and the testing Part are introduced first. The AFP systems consist of one 6 DOF serial manipulator, a small-size automated fiber placement head, the controller of the Fanuc Robot (6 DOF serial manipulator), pneumatic systems, and a Driver box. Then the experimental tests aim at demonstrating the AFP manufacturing process for a flat surface and also the process of manufacturing on the surface of a tight corner of several testing parts. The serial robots follow the code which is generated by the offline programming software on the computer connected to the controller. It is expected that the robot passes the flat surface tests and be able to deposit the layers on the inner surface of V-shaped structure.

5.2 Test setup

5.2.1 AFP systems setup

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

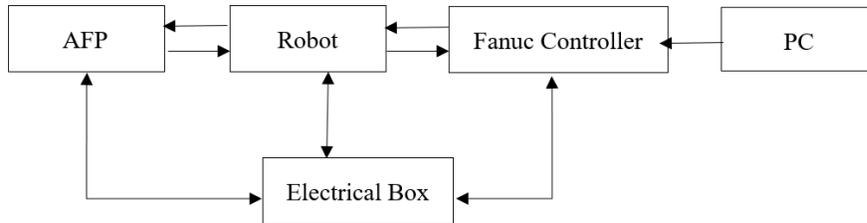


Figure 5-1 Hard drive structure

5.2.2 Testing setup for flat surface test

In order to conduct tests on a flat surface, a test table has been employed. For this test the robot is used to parallelly move the AFP head on a flat surface (laboratory desk).

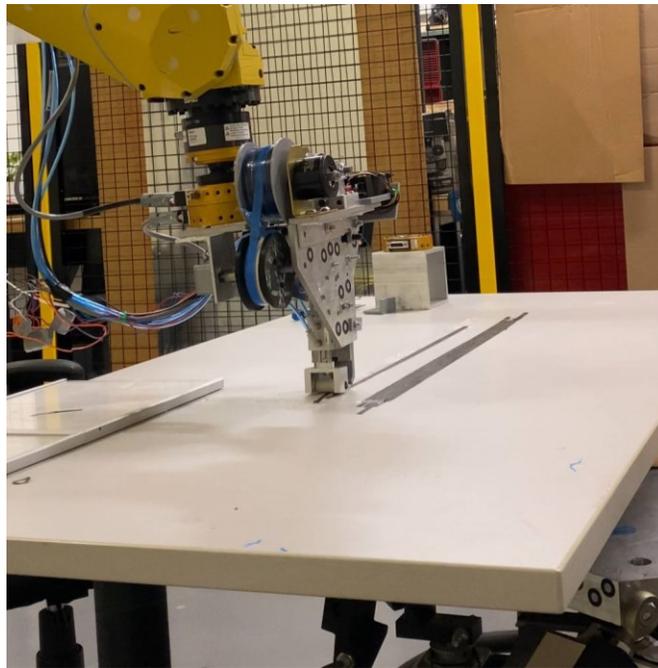


Figure 5-2 Test setup for Automated Fiber Placement on the flat surface

Different Modes have been implemented for the tests. By importing the desired gap and width, the developed algorithm was able to correctly calculate all of the points and the gaps between each layer. There was a need of grasping the tow manually before using the colling system but sometimes due to the heat emitted by the stepper motor, the Thermoset tows stuck on it.

5.2.3 Testing setup for the V-shape structure

In order to conduct tests on multiple parts with varying fillet radii and angles, an innovative approach was developed. This approach involved the creation of a unique testing part, which consists of two plexiglass sheets connected to a 3D-printed part in the middle. This design allows for easy interchangeability of the testing parts, as only the 3D printed part needs to be changed. The design was developed to save time and provide an easy-to-mount solution for the testing process.

To increase the stability of the structure, the bottom part of the testing part was fixed to the table, and the side part was mounted using aluminum parts on the backside. The use of aluminum parts not only increased the stability of the testing part but also allowed for easy adjustments during the testing process.

Overall, this innovative approach has proven to be a practical solution for conducting tests on multiple parts with varying fillet radii and angles. It has provided a time-saving and easy-to-mount solution for the testing process, while also ensuring stability and accuracy in the results obtained.



Figure 5-3 Photos of the testing setup for 85 degrees and a radius of 10mm

5.3 Experimental Test

5.3.1 Test for fiber placement on a flat surface

After giving the software the desired name, length, process mode, width, and speed of the process, the code with the same name is transferred to the Fanuc robot's controller. Then after running the code with the teach pendant, the robot starts to move toward the predefined first point. After that, the feeding system is activated which brings the tow under the roller. Then, the robot started to go to the second point and then the compaction system is activated so the layer sticks on the table. While the roller is applying pressure on the table, the robots start to move toward the next point at which the cutter is activated. After the cutter performs the cutting process, the robot continues the path to the last point where the layer ends. Then the second sequence starts to operate with the predefined gap. After a lot of tests, it was found that the robot is able to perform the fiber placement procedure on a flat surface without collision. By having the software, the operator is allowed to change and customize the sizes, the speed, and the number of sequences.

5.3.2 Test for fiber placement on the inner surface of V-shape structures

The research aims to design and develop a compact-size AFP that could perform fiber placement on V-shaped structures. In order to achieve this objective, the minimum values of angle and radius were determined in the previous chapter, and a test object was 3D printed based on these values.

Once the test object was fabricated, it was installed onto the test setup, and aluminum plates were attached to it to enhance its strength as it has been illustrated in Figure 5-4. This was a critical step in preparing the setup for the fiber placement process. As it is clear a back support has been also added and designed specifically for the 96-degree part in order to provide the required support for the part.

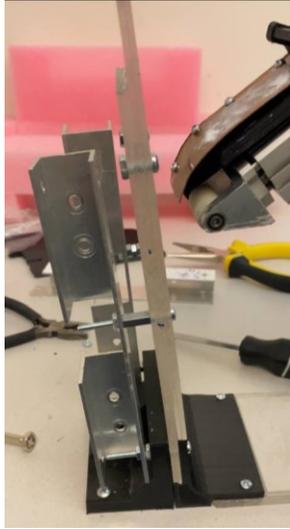


Figure 5-4 Test setup for 96 degrees test part

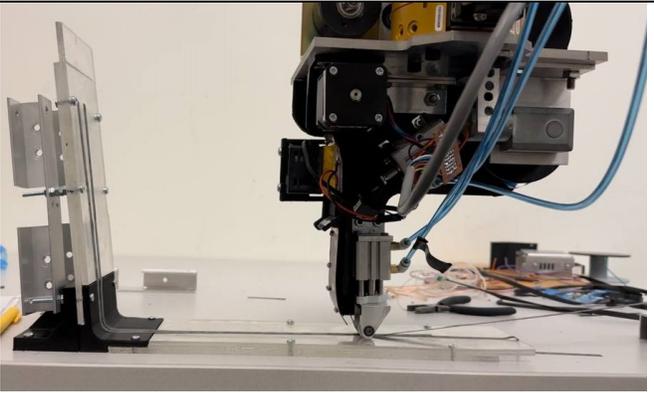
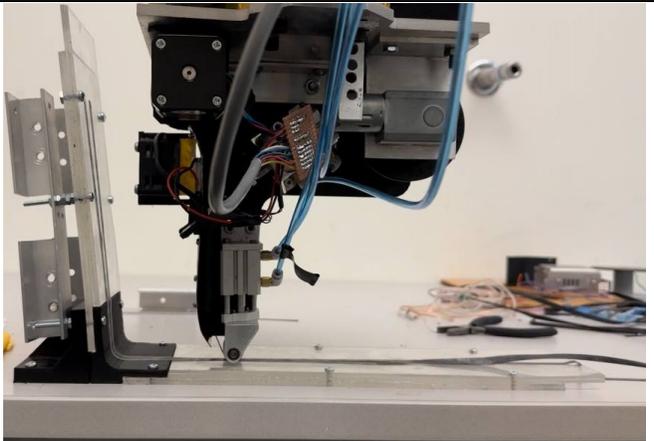
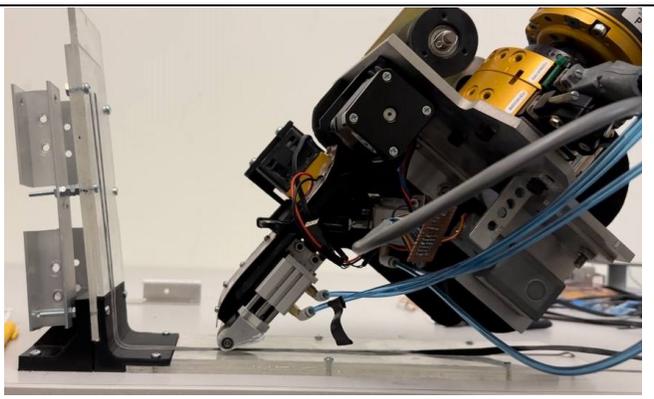
To facilitate the fiber placement process, a path planning algorithm was developed using the software, and it was added to the Robot using the Teach pendant. The algorithm allowed the AFP robot to rotate into the desired positions with predefined values, which ensured the accurate and precise placement of the fiber.

The path planning algorithm was executed successfully, and the AFP robot was able to deposit the fiber without any collisions with the table. This demonstrated the effectiveness of the developed AFP and the path planning algorithm in performing fiber placement on V-shaped structures.

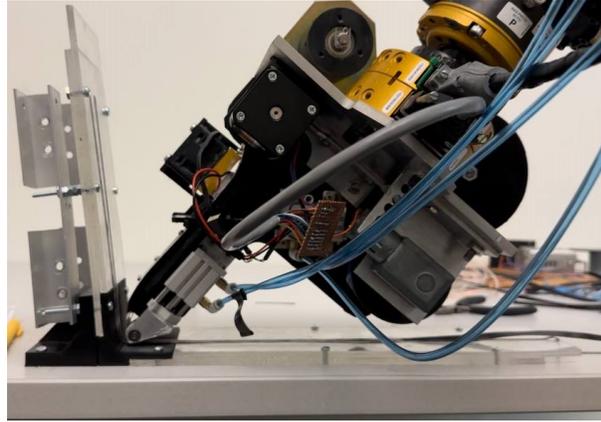
Overall, this research provided valuable insights into the development of a compact AFP for fiber placement on V-shaped structures. The successful execution of the fiber placement process has the potential to pave the way for further advancements in the field of AFP and could contribute to the development of new technologies and materials for various applications.

The steps of this experiment have been described in the Table 5-1. Additionally, the video of the following steps and experiment is available through this [link](#).

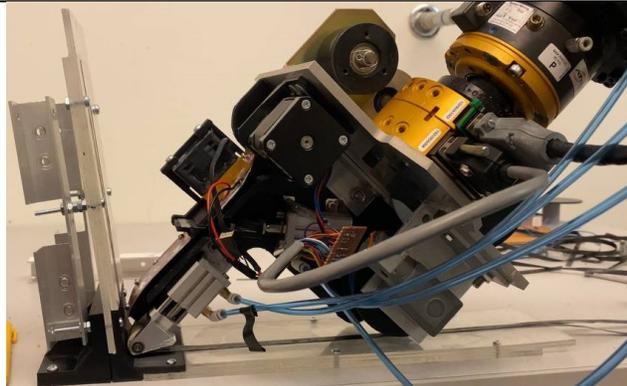
Table 5-1 Table of the Experimental test steps

<p>1-Robot starts from its first position and goes toward the first point on the part. At a point above that place, the feeding system feed the tape, and after reaching the first point it stops. It starts to go to the next point where the compaction system applies pressure from the roller to the part.</p>	
<p>2- The robot continues its path to reach the first rotation position.</p>	
<p>3-After reaching this point, the rotation of a predefined value has been done.</p>	

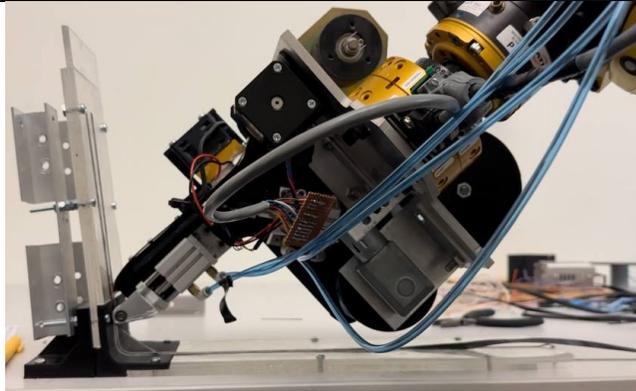
4-The robot continues its path to reach the middle point of the curve of the part which is basically the second rotation point.



5-Robot rotates for the second time with the predefined value.

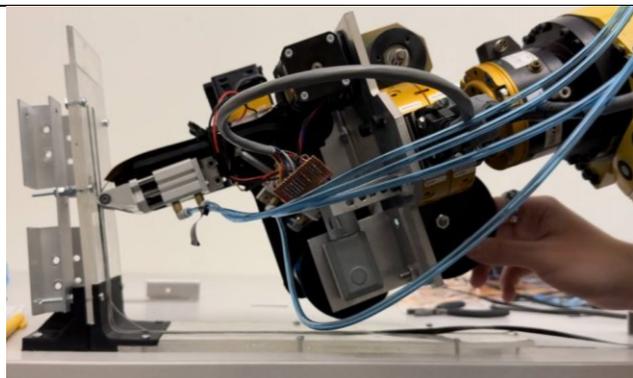


6- After the robot's second rotation, the robot follows its path in order to reach the third rotation point on the part.



7- Robot reaches the third point and rotates to the value which has been set earlier.

After this point, the cut is done and the robot follows its path till the end of the part to deposit the layer of fiber. After finishing its path, the robot goes back to the first(home) position.



It is worth mentioning that enlarging the radius and angle would undoubtedly simplify the procedure, making it infeasible for the AFP to collide with the surface. On the other hand, based on simulations, reducing the angle of the V-shape parts could increase the risk of collision, which would result in fewer tests being performed due to potential damage to the setup and the robot. Therefore, tests with smaller angles have not been conducted.

This experiment shows that the proposed AFP head is capable of performing small angles than the aforementioned available robots at Concordia University’s composites laboratory.

The following table also shows the Positions and Rotations value of the 96 degrees part fiber placement. It should be noted that the origin of the coordinates has been set to the robot's home position and orientation.

Table 5-2-Rotation values and the positions of rotations

Name	Positions (mm)	Rotation values and direction
First rotation Position	(1490.00,23.00,182.50)	-38.840
Second Rotation	(1490.00,99.00,182.50)	-43.00
Third Rotation	(1490.00,112.69,294.49)	-85.00

5.4 Summary

In this chapter, a brief summary of the test setup and experiments was described. The simulations results were validated, and the smallest possible angle and radius for the AFP to perform fiber placement on the inner surface of a V-shaped structure were determined through successful experiments. It was found that 96 degrees and 10mm of radius are the smallest values possible for the angle and radius of V-shape part based on the current available AFP and its CAD design.

It should be noted that any further changes beyond these values would require modifications to the CAD and simulation, followed by the experimental implementation to ensure the safety of the operator, robot, and setup. These modifications would need to be tested and validated through further experiments. By following these steps, the procedure can be conducted with the highest level of safety and accuracy possible.

Chapter 6

6 Conclusion, Contributions, and Recommendations for future works:

6.1 Conclusion

The use of composite materials has become prevalent in various industries, including aerospace, automobiles, wind turbines, civil infrastructures, and medical devices. However, the current automated fiber placement (AFP) machines are primarily designed for the production of shallow shells or tubes used for airframe components and are not capable of manufacturing more intricate shapes and tight shapes. To address this issue, this thesis proposes a small-size AFP system which can manufacture composite components with tight shapes and also flat shapes while improving production efficiency. The system comprises a 6 degrees of freedom (DOF) serial robot that holds the aforementioned fiber placement head to be able to deposit the layer on the surface. While in this thesis offline programming has been implemented. It is worth mentioning that the Reducing the AFP angle would allow the AFP head to deposit tows on a tighter angle.

- Rotations of the AFP are necessary to prevent collisions with the V-shape structure.
- Using a simulation environment instead of checking for collisions with the robot can improve safety for the operator and equipment, as well as speed up testing.

- Like other robotics projects, this project covers various related topics that require specialized knowledge and adding more members for such projects will increase the speed of the project.
- Replacing mechanical subsystems with more compact components can lead to a smaller-sized AFP.
- Utilizing a Solidworks plugin can streamline the part design process for simulations.
- Developing softwares based on the algorithms can improve the path planning procedure for the robot and the speed of its generation.
- Implementing cooling systems such as Peltier modules can prevent tapers from sticking without altering their mechanical properties.
- Using an electrical box like the driver box can simplify the process of activating and deactivating electrical subsystems due to their plug-and-play feature.
- Building a geometrical model helps determine the limitations of the AFP head.

6.2 Contributions

The major contributions of the research work are listed as follows:

- Redesigning the mechanical design of the AFP head in order to have the compact size
- Adding the cooling system in order to cool down the tapes to prevent the tape from sticking to guiding system
- Building a Driver box that connects to all of the main systems and subsystems
- Introducing the Solidworks plug-in which builds various models using Macro programming based on Virtual Basic language for the simulation environment
- Conducting the simulation of the whole procedure in a RoboDK simulation environment for fiber placement on the inner surface of V-shaped structures including the proposed AFP Head, Fanuc 6 DOF robot, and the testing parts
- Building the geometrical models of the AFP head and the tight V-shape part in order to utilize in the algorithms of controlling the Fanuc 6DOF serial manipulator
- Developing two offline programming path planning algorithms using RoboDK post-processor for depositing the layers on the flat surface and on the inner surface of V-shaped structures.
- Developing PC version software to implement the algorithm with GUI (Graphic user interface)
- Conducting the experimental tests of the AFP system for fiber placement procedure on the flat surface and V-shape part.

6.3 Future works

There are some recommended studies that need further investigations, which are listed below:

6.3.1 Different designs using Catia

As it is mentioned earlier, one of the methods of having a new design is to bring the cutting system to the left-hand side of the compaction system in order to bring the blade close to the tip and decrease the size of the guide system height. This will aim to have a smaller AFP head but a thicker tip as mentioned in Fig 6-1. Fig 6-3 also demonstrates an AFP head with two compaction systems which can lead to remove the feeding system.

To facilitate future research, the aforementioned modifications have been implemented in a new CAD design. Hence, the new design photos are in the following.

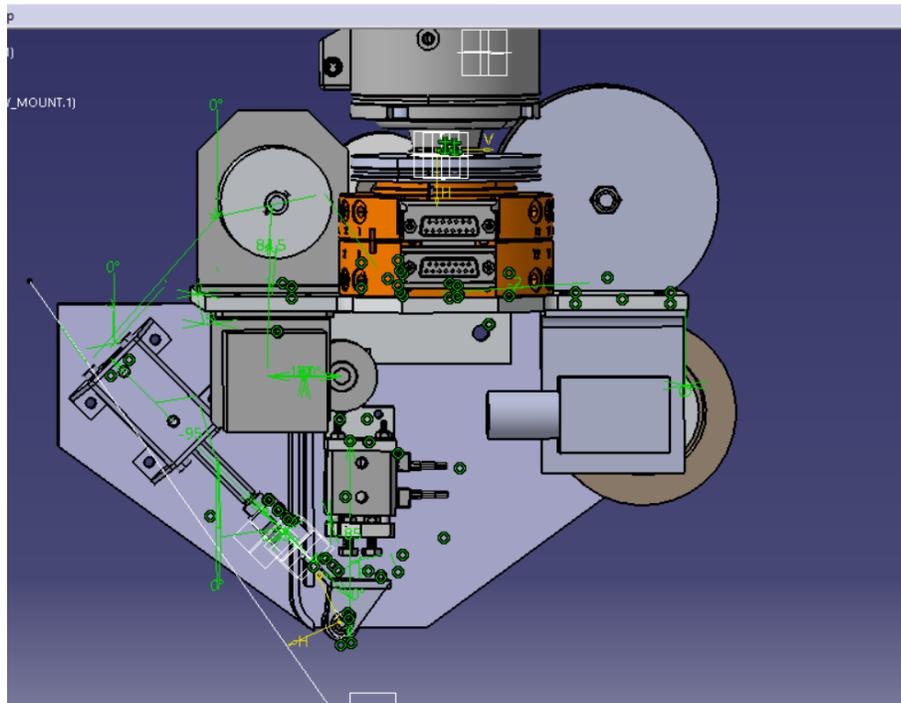


Figure 6-1 Version 8 CAD design

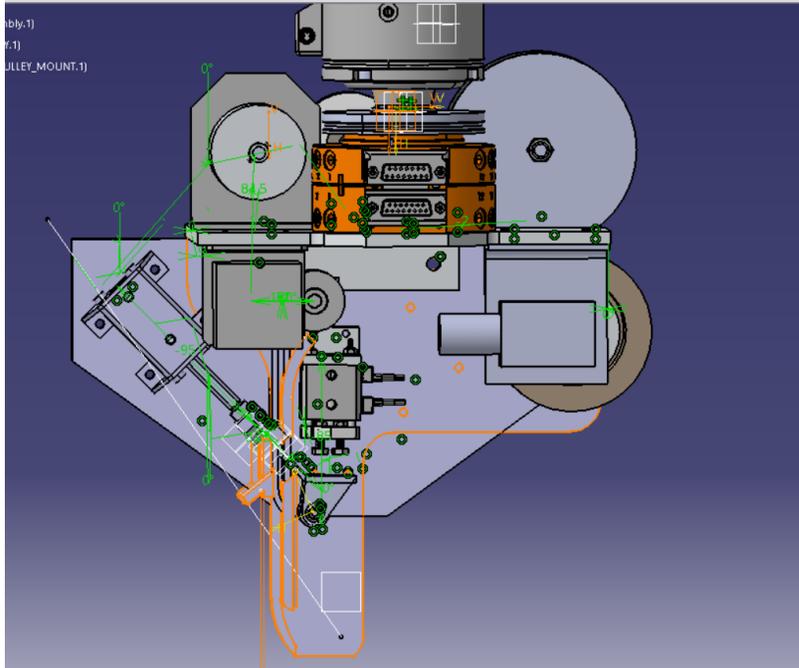


Figure 6-2 Version7 vs. Version 8 CAD design

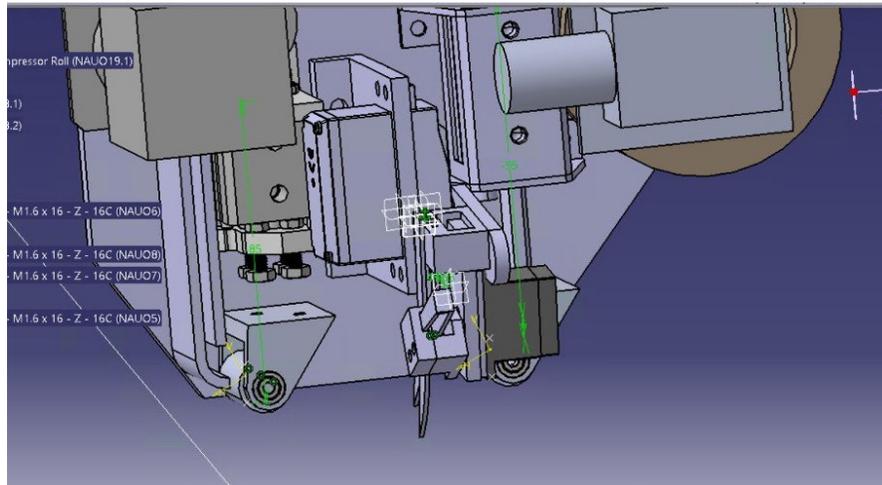


Figure 6-3 AFP head with 2 compaction systems

6.3.2 Cooling system

Even though the implemented cooling system is an innovative solution, it is also a temporary solution.

It is highly recommended for the researchers to work on different approaches to cool down the thermoset tape in order to prevent tackiness in the future.

6.3.3 Heating system

There is a need to heat the substrate layer in order to increase the cohesion between the printing layer and the substrate layers.

Since the stickiness of the thermoset layers will be activated upon providing a certain amount of heat, there could be a heating system to do so. This device can be a laser, an IR heater, or another small-size heating system.

6.3.4 Reachability of a tighter angle of V-shaped parts

In order to increase the reachability of the AFP head for tighter corners of V-shaped parts, several ways are suggested.

Increasing the H height of the AFP results in having a smaller AFP angle which led to reaching a smaller angle.

Decreasing the AFP angle by having a smaller compaction system or optimum space between the other components is also feasible.

6.3.5 Using a sensor for the feedback

In order to control the system properly a closed-loop feedback system is needed and to do so a highly precise sensor can be also used as the part missing in this loop. The sensor should detect the shape and the distance of the AFP and the part.

6.3.6 Using another robot to increase the DOF

As has been mentioned earlier in the literature review chapter, to increase the reachability and prevent the robot from rotate too much for fiber placement on V-shape parts, another robot like a parallel robot can be used to increase the DOF. It is worth noting that this will help to increase the pressure of the compaction roller on the part.

References

- [1] Groppe, D. (2000), "Robots improve the quality and cost-effectiveness of composite structures", *Industrial Robot*, Vol. 27 No. 2, pp. 96-102. [online]. Available: <https://doi.org/10.1108/01439910010315391> [Accessed: 13-April-2023]
- [2] M. Ahrens, V. Mallick and K. Parfrey, "Robotic based thermoplastic fibre placement process," Proceedings. 1998 *IEEE International Conference on Robotics and Automation* (Cat. No.98CH36146), Leuven, Belgium, 1998, pp. 1148-1153 vol.2, doi: 10.1109/ROBOT.1998.677247.
- [3] A. P. Singh, M. Sharma, and I. Singh, "A review of modeling and control during drilling of fiber reinforced plastic composites," *Compos B Eng*, vol. 47, pp. 118–125, Apr. 2013, doi: 10.1016/j.compositesb.2012.10.038.
- [4] Composites World, "The Markets: Aerospace (2015)," 12 1 2015. [Online]. Available: <http://www.compositesworld.com/articles/the-markets-aerospace-2015> [Accessed: 13-April-2023]
- [5] Boeing 787 Dreamliner "AERO - Boeing 787 from the Ground Up". [Online]. Available https://www.boeing.com/commercial/aeromagazine/articles/qtr_4_06/article_04_1.html [Accessed: 13-April-2023]
- [6] Aghababaei Tafreshi, Omid. "Heat Transfer Study of the In-situ Automated Fiber Placement (AFP) for Thermoplastic Composites." Master thesis, Concordia University, 2019. [online]. Available <https://spectrum.library.concordia.ca/id/eprint/986269/> [Accessed: 13-April-2023]
- [7] D. H. J. A. Lukaszewicz, C. Ward, and K. D. Potter, "The engineering aspects of automated prepreg layup: History, present and future," *Compos B Eng*, vol. 43, no. 3, pp. 997–1009, Apr. 2012, doi: 10.1016/j.compositesb.2011.12.003.

- [8] Ghayoor Karimiani, Hossein. "Analysis of residual stresses in thermoplastic composites manufactured by automated fiber placement." Master thesis, Concordia University, 2015. [online]. Available <https://spectrum.library.concordia.ca/id/eprint/980539/> [Accessed: 13-April-2023]
- [9] S. Zamotina, "FINAL CAPSTONE REPORT Team 10-FP Robot End Effector.", Capstone project, Concordia University, 2020.
- [10] Zhang, Xiaoming. "Modeling and Control of the Cooperative Automated Fiber Placement System." PhD diss., Concordia University, 2017. [online]. Available https://spectrum.library.concordia.ca/983359/1/Zhang_PhD_S2018.pdf [Accessed: 13-April-2023]
- [11] Gharabegi, Norvan. "Composite Laminates Made by Automated Fiber Placement of Dry Fibers and Vacuum Assisted Resin Transfer Molding." PhD diss., Concordia University, 2018. [online]. Available <https://spectrum.library.concordia.ca/id/eprint/983680/> [Accessed: 13-April-2023]
- [12] G. Dell'Anno *et al.*, "Automated manufacture of 3D reinforced aerospace composite structures," *International Journal of Structural Integrity*, vol. 3, no. 1, pp. 22–40, 2012, doi: 10.1108/17579861211209975.
- [13] Grimshaw, Michael N., Carroll G. Grant, and Jose Manuel Luna Diaz. "Advanced technology tape laying for affordable manufacturing of large composite structures." *In International sampe symposium and exhibition*, pp. 2484-2494. SAMPE; 1999, 2001.
- [14] W. ZHANG, F. LIU, T. JIANG, M. YI, W. CHEN, and X. DING, "Overview of current design and analysis of potential theories for automated fibre placement mechanisms," *Chinese Journal of Aeronautics*, vol. 35, no. 4. Elsevier B.V., pp. 1–13, Apr. 01, 2022. doi: 10.1016/j.cja.2021.04.018.
- [15] C. Grant, "Automated processes for composite aircraft structure," *Industrial Robot*, vol. 33, no. 2. pp. 117–121, 2006. doi: 10.1108/01439910610651428.

- [16] Madhok, Kulbir Singh. "Comparative characterization of Out-of-Autoclave Materials made by Automated Fiber Placement and Hand-Lay-Up Processes." PhD diss., Concordia University, 2013.
- [17] L. Izco, J. Isturiz, and M. Motilva, "High speed tow placement system for complex surfaces with cut/clamp/& restart capabilities at 85 m/min (3350 IPM)," *Additive Manufacturing of Aerospace Composite Structures: Fabrication and Reliability*, vol. 181, p. 1, 2017.
- [18] L. Sorrentino, L. Carrino, L. Tersigni, and A. Leone, "Innovative tape placement robotic cell: High flexibility system to manufacture composite structural parts with variable thickness," *J Manuf Sci Eng*, vol. 131, no. 4, pp. 0410021–0410028, 2009, doi: 10.1115/1.3160594.
- [19] Addcomposites product page "Addcomposites - Plug and Place AFP". [online]. Available: <https://www.addcomposites.com/afpxs> [Accessed: 13-April-2023]
- [20] G. Marsh, "Automating aerospace composites production with fibre placement," *Reinforced Plastics*, vol. 55, no. 3, pp. 32–37, May 2011, doi: 10.1016/S0034-3617(11)70075-3.
- [21] W. Xie, "Design and Analysis of Collaborative Automated Fiber Placement Machine," *International Journal of Advanced Robotics and Automation*, vol. 1, no. 1, pp. 01–14, Mar. 2016, doi: 10.15226/2473-3032/1/1/00105.
- [22] 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. CAD Solutions, LLC, pp. 172–203, 2019. doi: 10.14733/cadaps.2019.172-203.
- [23] Goldsworthy WB. Geodesic path length compensator for composite-tape placement method. United States patent US 3810805. 1974 May 14.
- [24] Pugh JH, inventor. Strand laying head. United States patent US 4569716. 1986 Feb 11.
- [25] Vaniglia MM, inventor. Fiber placement head. United States patent US 5110395. 1992 May 5.

- [26] W. Zhang, F. Liu, Y. Lv, and X. Ding, "Modelling and layout design for an automated fibre placement mechanism," *Mech Mach Theory*, vol. 144, Feb. 2020, doi: 10.1016/j.mechmachtheory.2019.103651.
- [27] Tingley, Mark Curtis. "Add roller for a fiber placement machine." U.S. Patent 7,628,882, issued December 8, 2009.
- [28] T. Oldani and D. Jarvi, "Performing high-speed events 'on-the-fly' during fabrication of a composite structure by automated fiber placement." Google Patents, Apr. 07, 2009.
- [29] Vaniglia, Milo M. "Motorized cut and feed head." U.S. Patent 7,849,903, issued December 14, 2010.
- [30] B. Denkena, C. Schmidt, and P. Weber, "Automated Fiber Placement Head for Manufacturing of Innovative Aerospace Stiffening Structures," *Procedia Manuf*, vol. 6, pp. 96–104, 2016, doi: 10.1016/j.promfg.2016.11.013.
- [31] M. Steeg, R. Schledjewski, and A. K. Schlarb, "Automation implementation and process development of thermoplastic tape placement for 3-dimensional parts," *SAMPE journal*, vol. 42, no. 5, pp. 18–24, 2006.
- [32] Zacchia, Tom Trung, Farjad Shadmehri, Jeffrey Fortin-Simpson, and Suong Van Hoa. "Design of hard compaction rollers for automated fiber placement on complex mandrel geometries." CSME Conference Processing (2018). [online]. Available: <https://yorkspace.library.yorku.ca/xmlui/handle/10315/35245>
- [33] I. de Jesus Gonzalez Ojeda, O. Patrouix, and Y. Aoustin, "Pressure based approach for Automated Fiber Placement (AFP) with sensor-based feedback loop and flexible component in the effector," in *IFAC-PapersOnLine*, Elsevier B.V., Jul. 2017, pp. 794–799. doi: 10.1016/j.ifacol.2017.08.511.
- [34] T. Aized and B. Shirinzadeh, "Robotic fiber placement process analysis and optimization using response surface method," *International Journal of Advanced Manufacturing Technology*, vol. 55, no. 1–4, pp. 393–404, Jul. 2011, doi: 10.1007/s00170-010-3028-1.

- [35] N. Bakhshi and M. Hojjati, "Effect of compaction roller on layup quality and defects formation in automated fiber placement," *Journal of Reinforced Plastics and Composites*, vol. 39, no. 1–2, pp. 3–20, Jan. 2020, doi: 10.1177/0731684419868845.
- [36] Veldenz, Laura, Mattia Di Francesco, Simon Astwood, Giuseppe Dell'Anno, Byung Chul Kim, and Kevin Potter. "Characteristics and processability of bindered dry fibre material for automated fibre placement." In 17th European Conference on Composite Materials. 2016. [online]. Available: https://www.researchgate.net/profile/Laura-Veldenz/publication/304896784_CHARACTERISTICS_AND_PROCESSABILITY_OF_BINDERED_DRY_FIBRE_MATERIAL_FOR_AUTOMATED_FIBRE_PLACEMENT/links/577cd2cf08aece6c20fe172e/CHARACTERISTICS-AND-PROCESSABILITY-OF-BINDERED-DRY-FIBRE-MATERIAL-FOR-AUTOMATED-FIBRE-PLACEMENT.pdf [Accessed: 13-April-2023]
- [37] A. Trochez, V. C. Jamora, R. Larson, K. C. Wu, D. Ghosh, and O. G. Kravchenko, "Effects of automated fiber placement defects on high strain rate compressive response in advanced thermosetting composites," *J Compos Mater*, vol. 55, no. 30, pp. 4549–4562, Dec. 2021, doi: 10.1177/00219983211042073.
- [38] K. Fayazbakhsh, M. Arian Nik, D. Pasini, and L. Lessard, "Defect layer method to capture effect of gaps and overlaps in variable stiffness laminates made by Automated Fiber Placement," *Compos Struct*, vol. 97, pp. 245–251, Mar. 2013, doi: 10.1016/j.compstruct.2012.10.031.
- [39] R. H. Rizzolo and D. F. Walczyk, "Ultrasonic consolidation of thermoplastic composite prepreg for automated fiber placement," *Journal of Thermoplastic Composite Materials*, vol. 29, no. 11, pp. 1480–1497, Nov. 2016, doi: 10.1177/0892705714565705.
- [40] B. Shirinzadeh, G. Alici, C. W. Foong, and G. Cassidy, "Fabrication process of open surfaces by robotic fibre placement," *Robot Comput Integr Manuf*, vol. 20, no. 1, pp. 17–28, Feb. 2004, doi: 10.1016/S0736-5845(03)00050-4.
- [41] L. Li, D. Xu, X. Wang, and M. Tan, "A survey on path planning algorithms in robotic fibre placement," in *Proceedings of the 2015 27th Chinese Control and Decision Conference*,

- CCDC 2015*, Institute of Electrical and Electronics Engineers Inc., Jul. 2015, pp. 4704–4709. doi: 10.1109/CCDC.2015.7162756.
- [42] Hornick, Mark L., and Bahram Ravani. "Computer-aided off-line planning and programming of robot motion." *The International journal of robotics research* 4, no. 4 (1986): 18-31.
- [43] B. Shirinzadeh, C. W. Foong, and B. H. Tan, "Robotic fibre placement process planning and control," *Assembly Automation*, vol. 20, no. 4, pp. 313–320, 2000, doi: 10.1108/01445150010353242.
- [44] 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," *Robot Comput Integr Manuf*, vol. 30, no. 3, pp. 277–286, 2014, doi: 10.1016/j.rcim.2013.10.007.
- [45] C. S. Lopes, Z. Gürdal, and P. P. Camanho, "Variable-stiffness composite panels: Buckling and first-ply failure improvements over straight-fibre laminates," *Comput Struct*, vol. 86, no. 9, pp. 897–907, May 2008, doi: 10.1016/j.compstruc.2007.04.016.
- [46] "Simulator for industrial robots and offline programming - RoboDK". [Online]. Available: <https://robodk.com/index>
- [47] S. Pieskä, J. Kaarela, and J. Mäkelä, "Simulation and programming experiences of collaborative robots for small-scale manufacturing," in *2018 2nd International Symposium on Small-Scale Intelligent Manufacturing Systems, SIMS 2018*, Institute of Electrical and Electronics Engineers Inc., May 2018, pp. 1–4. doi: 10.1109/SIMS.2018.8355303.
- [48] P. Sivasankaran* and R. Karthikeyan, "Simulation of Robot Kinematic Motions using Collision Mapping Planner using Robo Dk Solver," *International Journal of Innovative Technology and Exploring Engineering*, vol. 9, no. 11, pp. 21–27, Sep. 2020, doi: 10.35940/ijitee.J7588.0991120.
- [49] "Thermoelectric Cooler Performance Specifications Mechanical Drawing : ." [Online]. Available: <https://wellentech.en.made-in-china.com/product/BovxSyDJZiKA/China-Thermoelectric-Modules-TEs1-12704-.html> [Accessed: 13-April-2023]

[50] “TB6600 Stepper Motor Driver with Arduino Tutorial”. [Online]. Available: <https://www.makerguides.com/tb6600-stepper-motor-driver-arduino-tutorial/> [Accessed: 13-April-2023]

Appendix B

```
#define dirPin 6
#define stepPin 7
#define PLCPin 9
#define stepsPerRevolution 200

void setup() {
  // Declare pins as output:
  pinMode(stepPin, OUTPUT);
  pinMode(dirPin, OUTPUT);
}

void loop() {

  while (digitalRead (PLCPin) == LOW) {
    digitalWrite(stepPin, LOW);
    delayMicroseconds(500);
  }

  digitalWrite(dirPin, LOW);
  for (int i = 0; i < 4000; i++) {
    // These four lines result in 1 step:
    digitalWrite(stepPin, HIGH);
    delayMicroseconds(500);
    digitalWrite(stepPin, LOW);
    delayMicroseconds(500);
  }
  delay(2000);
}
```

Appendix C

```
' *****
' C:\Temp\swx11428\Macro1.swb - macro recorded on 07/22/22 by A_SABOUK
' *****
Dim swApp As Object

Dim Part As Object
Dim boolstatus As Boolean
Dim longstatus As Long, longwarnings As Long

Sub main()

UserForm1.Show

End Sub

Public Sub AFP(a As Integer, b As Integer, c As Integer, e As Integer, f As Integer, g As Integer)
'=====

    Dim i As Integer
    Dim j As Integer
    For i = a To b Step c
    For j = e To f Step g
    Set swApp = Application.SldWorks

    Set Part = swApp.ActiveDoc
    Dim COSMOSWORKSObj As Object
    Dim CWAddinCallBackObj As Object
    Set CWAddinCallBackObj = swApp.GetAddInObject("CosmosWorks.CosmosWorks")
    Set COSMOSWORKSObj = CWAddinCallBackObj.COSMOSWORKS
    Dim d As Double
    alpha = (3.141592 * i) / 180
    alphaR = i
    h = alpha / 2
    d = (Cos(h) / Sin(h)) * 1 / 100
    R = j / 100
    RR = j
    Dim name As String
    u = CStr(alphaR)
    k = CStr(RR)
    name = "part_" & u & "_" & k
    ' New Document
    Dim swSheetWidth As Double
    swSheetWidth = 0
    Dim swSheetHeight As Double
    swSheetHeight = 0
    Set Part = swApp.NewDocument("C:\ProgramData\SolidWorks\SOLIDWORKS
2021\templates\Part.PRTDOT", 0, swSheetWidth, swSheetHeight)
    Dim swPart As PartDoc
    Set swPart = Part
    swApp.ActivateDoc2 "Part15", False, longstatus
    Set Part = swApp.ActiveDoc
    Part.SketchManager.InsertSketch True
    boolstatus = Part.Extension.SelectByID2("Right Plane", "PLANE", -7.85822654783262E-02,
4.43794772713645E-03, 3.84517142947887E-02, False, 0, Nothing, 0)
    Part.ClearSelection2 True
    Dim skSegment As Object
    Set skSegment = Part.SketchManager.CreateLine(0#, 0#, 0#, 0.2 + d, 0#, 0#)
    Set skSegment = Part.SketchManager.CreateLine(0.2 + d, 0#, 0#, 0.2 + d, -0.01, 0#)
    Set skSegment = Part.SketchManager.CreateLine(0.2 + d, -0.01, 0#, d, -0.01, 0#)
    Set skSegment = Part.SketchManager.CreateLine(d, -0.01, 0#, 0.2 * Cos(pi - alpha) + d,
0.2 * Sin(pi - alpha) - 0.01, 0#)
```

```

    Set skSegment = Part.SketchManager.CreateLine(0.2 * Cos(pi - alpha) + d, 0.2 * Sin(pi -
alpha) - 0.01, 0#, 0.2 * Cos(pi - alpha) + d + 0.01 * Sin(pi - alpha), 0.2 * Sin(pi - alpha)
- 0.01 - 0.01 * Cos(pi - alpha), 0#)
    Set skSegment = Part.SketchManager.CreateLine(0.2 * Cos(pi - alpha) + d + 0.01 * Sin(pi
- alpha), 0.2 * Sin(pi - alpha) - 0.01 - 0.01 * Cos(pi - alpha), 0#, 0#, 0#, 0#)

' line fix
Part.ClearSelection2 True
boolstatus = Part.Extension.SelectByID2("Line6", "SKETCHSEGMENT", -1.92779759972826E-02,
-1.68682289976223E-02, 0, False, 0, Nothing, 0)
boolstatus = Part.Extension.SelectByID2("Line4", "SKETCHSEGMENT", -1.36275347566998E-02,
-0.027005785341021, 0, True, 0, Nothing, 0)
Part.SketchAddConstraints "sgPARALLEL"
Part.ClearSelection2 True

' Fillet
boolstatus = Part.Extension.SelectByID2("Line4", "SKETCHSEGMENT", -4.9308347668767E-03,
0, 2.12495498286829E-02, True, 0, Nothing, 0)
boolstatus = Part.Extension.SelectByID2("Line3", "SKETCHSEGMENT", 2.46541738343834E-02,
0, 1.18574836060606E-02, True, 0, Nothing, 0)
Set skSegment = Part.SketchManager.CreateFillet(R, 1)

' Named View
Part.ShowNamedView2 "*Trimetric", 8
Part.ViewZoomtofit2
Dim myFeature As Object
Set myFeature = Part.FeatureManager.FeatureExtrusion2(False, False, False, 0, 0, 0.1,
0.1, False, False, False, 1.74532925199433E-02, 1.74532925199433E-02, False, False,
False, False, True, True, True, 0, 0, False)
Part.SelectionManager.EnableContourSelection = False
boolstatus = Part.Extension.SelectByRay(0.073301012185425, 3.42077641533365E-02,
1.30075596665051E-02, -0.400036026779312, -0.515038074910024, -0.758094294050284,
1.11017495529131E-03, 2, False, 0, 0)
Part.SketchManager.InsertSketch True
Part.ClearSelection2 True
Set skSegment = Part.SketchManager.CreateCircle(0.15, 0.05, 0#, 0.154, 0.05, 0#)
Part.ClearSelection2 True
Set skSegment = Part.SketchManager.CreateCircle(0.15, -0.05, 0#, 0.154, -0.05, 0#)

' Previous View
Part.ViewOrientationUndo
Set myFeature = Part.FeatureManager.FeatureCut4(False, False, False, 0, 0, 0.1, 0.1,
False, False, False, False, 1.74532925199433E-02, 1.74532925199433E-02, False, False, False,
False, False, True, True, True, False, 0, 0, False, False)
Part.SelectionManager.EnableContourSelection = False

' Save As
longstatus = Part.SaveAs3("G:\thesis\yasaman\" & name & ".STEP", 0, 2)

' Close Document
Set swPart = Nothing
Set Part = Nothing
swApp.CloseDoc name
Set Part = swApp.ActiveDoc
Dim myModelView As Object
Set myModelView = Part.ActiveView
myModelView.FrameLeft = 0
myModelView.FrameTop = 0
Set myModelView = Part.ActiveView
myModelView.FrameState = swWindowState_e.swWindowMaximized
swApp.ActivateDoc2 "Part1", False, longstatus
Set Part = swApp.ActiveDoc
'StudyManagerObj = Nothing
'ActiveDocObj = Nothing
'Set CWAddinCallBackObj = Nothing
'Set COSMOSWORKSObj = Nothing

Next j
Next i
End Sub

```

Appendix D

```
# https://robodk.com/doc/en/RoboDK-API.html
import sys # allows getting the passed argument parameters
import openpyxl
import pandas as pd
import time
import numpy as np
from robodk.robolink import *
from robodk.robomath import *
from robodk.robodialogs import *
from robodk.robofileio import *

RDK = Robolink()

def longest(lst):
    maxList = max(lst, key=lambda i: len(i))
    return maxList

robot = RDK.Item('', ITEM_TYPE_ROBOT)
if not robot.Valid():
    raise Exception("Robot not available")

trialnumber = 2
path = (r'C:\Users\erman\OneDrive\Masaüstü\test\results.xlsx')
wb_obj = openpyxl.load_workbook(path)
sheet_obj = wb_obj.active

for deg in range(96, 131, 10):
    for r in range(1, 6, 2):
        RDK.setCollisionActive(check_state=0)
        filename = "Part_{}_{}.step".format(deg, r)
        filename1 = "Part_{}_{}".format(deg, r)
        degr = (deg * pi) / 180
        gamma = (122 * pi) / 180
        gamma2 = (138 * pi) / 180
        alpha = (48 * pi) / 180
        beta = (47 * pi) / 180
        table = RDK.Item("Frame Snap")
        part = RDK.AddFile(r'C:\Users\erman\OneDrive\Masaüstü\test\yasaman\{}'.format(filename),
table)
        part = RDK.Item(filename1)
        pose = Fanuc_2_Pose([-50.00, 159.004, -10.00, -90.00, 0.00, -90.0])
        part.setGeometryPose(pose, apply=True)

        print("I am already here")

        curvel_list = []
        a = 0
        while True:
            curve_points, name_feature = part.GetPoints(FEATURE_CURVE, a)
            if len(curve_points) == 0:
                break
            a = a + 1
            curvel_list.append(curve_points)

        curve_list = []
        for curve in curvel_list:
            for idx in range(len(curve)):
                x, y, z, i, j, k = curve[idx][0:6]
                if x == -150 and 1.0 < z < 40 and y < 150: # x == -150 and 1.0 < z < 40 and y <
135
                    curve_list.append(curve)
                    curve[idx][0:6] = [x + 10, y, z, i, j, 1]
```

```

curve_new = None
for curve in curve_list:
    curve_new = RDK.AddCurve(curve, curve_new, True, PROJECTION_NONE)

curve_new.setName(part.Name() + " New")
part1 = RDK.Item("Part_{ } New".format(deg, r))
curve_new.setParent(part.Parent())
curve_new.setGeometryPose(curve_new.GeometryPose())
curve_new.setValue('Display', 'LINEW=4')
part.setParam("DeleteCurves")

curve_list = []
ex = 0
while True:
    curve_points, name_feature = part1.GetPoints(FEATURE_CURVE, ex)
    if len(curve_points) == 0:
        break
    curve_proj_points = RDK.ProjectPoints(curve_points, part, PROJECTION_CLOSEST_RECALC)
    curve_list.append(curve_proj_points)
    ex = ex + 1

curvef_list = []
which = longest(curve_list)
curvef_list.append(which)

[mp_y, mp_z] = curve[len(curve) // 2][1:3]
y_end_y = 151 * abs(sin(degr - (pi / 2))) + mp_y + 11
y_end_z = 151 * abs(cos(degr - (pi / 2))) + mp_z
y_start = 70 + (112.827 / (sin(degr) / cos(degr)))
print(mp_y)
print(mp_z)
# critical angels are assumed to be 90 &
for curve in curvef_list:
    for idx in range(len(curve)):
        x, y, z, i, j, k = curve[idx][0:6]
        if 90 < degr < 131:
            if (y < y_start):
                if k < 0:
                    x, y, z, i, j, k = curve[idx][0:6]
                    curve[idx][0:6] = [x, y, z, i, j, -k]
                x, y, z, i, j, k = curve[idx][0:6]
                curve[idx][0:6] = [x, y + 7.5 * j, z + 7.5 * k, i, j, k]
            if (y_start < y <= mp_y):
                if k < 0:
                    x, y, z, i, j, k = curve[idx][0:6]
                    curve[idx][0:6] = [x, y, z, i, -j, -k]
                x, y, z, i, j, k = curve[idx][0:6]
                curve[idx][0:6] = [x, y + 7.5 * j, z + 7.5 * k, i, j, k]
                x, y, z, i, j, k = curve[idx][0:6]
                curve[idx][0:6] = [x, y, z, i, -sin(beta - degr + (pi / 2)), cos(beta -
degr + (pi / 2))]
            if (mp_y < y < y_end_y):
                if k < 0:
                    x, y, z, i, j, k = curve[idx][0:6]
                    curve[idx][0:6] = [x, y, z, i, -j, -k]
                x, y, z, i, j, k = curve[idx][0:6]
                curve[idx][0:6] = [x, y + 7.5 * j, z + 7.5 * k, i, j, k]
                x, y, z, i, j, k = curve[idx][0:6]
                curve[idx][0:6] = [x, y, z, i, -cos(1.13 * beta - degr + (pi / 2)),
sin(1.13 * beta - degr + (pi / 2))]
            if (y > y_end_y):
                x, y, z, i, j, k = curve[idx][0:6]
                curve[idx][0:6] = [x, y + 7.5 * j, z + 7.5 * k, i, j, k]
        if deg >= 131 and k < 0:
            curve[idx][0:6] = [x, y, z, i, -j, -k]

[x, y, z, i, j, k] = curve[0][0:6]
curve[0][0:6] = [x, y, z, 0, 0, 1]
[x, y, z, i, j, k] = curve[len(curve) - 1][0:6]
curve[len(curve) - 1][0:6] = [x, y, z, 0, -sin(degr), -cos(degr)]

```

```

curve_proj = None
for curve in curvef_list:
    curve_proj = RDK.AddCurve(curve, curve_proj, True, PROJECTION_NONE)

curve_proj.setName(part.Name() + " New2")
part2 = RDK.Item("Part_{ }_{} New2".format(deg, r))
curve_proj.setParent(part.Parent())
curve_proj.setGeometryPose(curve_proj.GeometryPose())
curve_proj.setValue('Display', 'LINEW=4')
RDK.Delete(part1)

RDK.setCollisionActive(check_state=1)

path2tool = Fanuc_2_Pose([0.00, 0.00, 0.00, 0.00, 0.00, 180.0])
path = RDK.AddMachiningProject(name="AFP")
path.setPose(path2tool)
path.setMachiningParameters(part=part2, params="SpeedOperation 50")

toolhead = RDK.Item("Product8withoutroller")
trialpart = RDK.Item(filename1)
RDK.setCollisionActivePair(COLLISION_ON, toolhead, trialpart)

pause(5)

prog = RDK.Item("AFP", itemtype=8)
RDK.setRunMode(RUNMODE_SIMULATE)
prog.RunCode()
prog.WaitFinished()
iscollided = RDK.Collision(toolhead, trialpart)

if iscollided == 1:
    result = "Yes"
else:
    if iscollided == 0:
        result = "No"
    else:
        pass

cell = sheet_obj.cell(row=trialnumber, column=1)
cell.value = filename1
cell = sheet_obj.cell(row=trialnumber, column=2)
cell.value = deg
cell = sheet_obj.cell(row=trialnumber, column=3)
cell.value = r / 10
cell = sheet_obj.cell(row=trialnumber, column=4)
cell.value = result

trialnumber = trialnumber + 1

wb_obj.save(r'C:\Users\erman\OneDrive\Masaüstü\test\results.xlsx')

part2.Delete()
prog.Delete()
part.Delete()
path.Delete()

RDK.setCollisionActive(check_state=0)
target = RDK.Item("Target 1")
robot.MoveJ(target)

print("Done!")

```

Appendix E

```
# This file is used by your post processor (Fanuc_RJ3_DripFeed) and edition of Alireza Saboukhi
# to generate the appropriate file for your robot.
# You will find your robot program in the same folder where this file is located.
# To avoid showing this file after program generation you can select:
# Tools->Options->tab Other, then, uncheck "Show programs in Notepad"

import sys
import os
from datetime import datetime
import time
from tkinter import *
#from robolink import * # RoboDK API
#from robodk import * # Robot toolbox

# datetime object containing current date and time
now = datetime.now()
# dd/mm/YY H:M:S
dt_string = now.strftime("%d/%m/%Y %H:%M:%S")

# Set up default parameters
PROGRAM_NAME = "Hi" # Name of the program
SPEED_RATE = 50 # Speed in mm/s of the welding path
LENGTH_VAL = 500 # Length of the surface
WIDTH_VAL = 100 # Width of the surface
def RunProgram():
    # Use default global variables
    global PROGRAM_NAME
    global SPEED_RATE
    global LENGTH_VAL
    global WIDTH_VAL

# Create Instance of Tkinter
# Generate the main window
app = Tk()
app.title("AFP application by Alireza Saboukhi")
Label(app, text="Hello, Please insert your desired values and name",
background="#34A2FE").pack()
entry_name = StringVar()
entry_name.set(PROGRAM_NAME)

entry_speed = StringVar()
entry_speed.set(str(SPEED_RATE))

entry_length = StringVar()
entry_length.set(str(LENGTH_VAL))

entry_width = StringVar()
entry_width.set(str(WIDTH_VAL))
#win.configure(background='#4D4D4D')
app.minsize(640, 400)
app.wm_iconbitmap('1552.ico')
#L1=Label(root, text="Program name")
Label(app, text="Program name").pack()
Entry(app, textvariable=entry_name).pack()
# Define a label and entry text for the speed
Label(app, text=" speed (mm/s)").pack()
Entry(app, textvariable=entry_speed).pack()
# Define a label and entry text for Length
Label(app, text=" Desired Length").pack()
Entry(app, textvariable=entry_length).pack()
# Define a label and entry text for Width
Label(app, text=" Desired Width").pack()
```

```

Entry(app, textvariable=entry_width).pack()
#L1.pack( side = LEFT)
#E1 = Entry(app, bd =5)
#E1.pack(side = RIGHT)
#B1=Button(app,text="salam")
#B1.pack()
clicked=StringVar()
clicked.set("Please choose your performance mode")
drop=OptionMenu(app,clicked,"Normal","Fast Mode","Test mode")
drop.pack()
clicked1=StringVar()
clicked1.set("Please select the gap size")
drop1=OptionMenu(app,clicked1,"zero offset","1 mm offset","2 mm offset")
drop1.pack()
#Start GUI
def ExecuteChoice():
    #global DRY_RUN
    #global RUN_MODE
    global SPEED_RATE
    global PROGRAM_NAME
    global LENGTH_VAL
    global WIDTH_VAL
    #DRY_RUN = dryrun.get()
    #RUN_MODE = runmode.get()
    SPEED_RATE = float(entry_speed.get())
    PROGRAM_NAME = entry_name.get()
    LENGTH_VAL=float(entry_length.get())
    WIDTH_VAL=float(entry_width.get())
    # Run the main program once all the global variables have been set
    RunProgram()

Button(app, text='Generate', command=ExecuteChoice).pack()
Button(app, text='Done!', command=app.destroy).pack()
app.mainloop()
#####
sys.path.append(os.path.abspath(r""C:/RoboDK/Posts/"")) # temporarily add path to POSTS
folder
print(clicked.get())
Answer=str(clicked.get())
Answer1=str(clicked1.get())
from Fanuc_RJ3_DripFeed import *

def p(x,y,z,r,p,w):
    a = r*math.pi/180.0
    b = p*math.pi/180.0
    c = w*math.pi/180.0
    ca = math.cos(a)
    sa = math.sin(a)
    cb = math.cos(b)
    sb = math.sin(b)
    cc = math.cos(c)
    sc = math.sin(c)
    return Mat([[cb*ca,ca*sc*sb-cc*sa,sc*sa+cc*ca*sb,x],[cb*sa,cc*ca+sc*sb*sa,cc*sb*sa-
ca*sc,y],[-sb,cb*sc,cc*cb,z],[0.0,0.0,0.0,1.0]])
#defining variables
X0=1165.454
X1=94*2# Offset of rotation for X direction
Y0=-27
Y1=94*2# Offset of rotation for Y direction
#Z0=270.794
Z0=480.586# before it was 480 and 465
W0=179.673
P0=0.091
R0=73.588
T0=120
Pr=90
Inz=450#insurance for z direction
Iny=200#insurance for y direction
Y=LENGTH_VAL
F=6#mm/fibre width approx.
if Answer1=="zero offset":

```

```

t=F
if Answer1=="1 mm offset":
    t=F+1
if Answer1=="2 mm offset":
    t=F+2
print('Total instructions: 5')
#RDK = Robolink()#initialize the ROBODK API
#RDK.setRunMode()
#robot=RDK.ItemUserPick("select a robot",ITEM_TYPE_ROBOT)
# tool=RDK.ItemUserPick("select a tool in robot",ITEM_TYPE_TOOL)
#robot.Connect()
#connected,message=robot.ConnectedState()
#print("connection status:")
# print(message)
r = RobotPost(r""Fanuc_RJ3_DripFeed"",r"" Fanuc M-20iA"",6,
axes_type=['R','R','R','R','R','R'], ip_com=r""192.168.0.10"", api_port=20500,
prog_ptr=419758960, robot_ptr=278881424)
number_of_width=int(WIDTH_VAL/F)#bayad addad tabbei baashe

r.ProgStart(PROGRAM_NAME)
r.RunMessage(r""Program generated by Alireza Saboukhi RoboDK v5.2.1 for Fanuc M-20iA on
"",True)
r.RunMessage(dt_string ,True)
r.RunMessage(clicked.get() ,True)
r.RunMessage(clicked1.get() ,True)
r.RunMessage(r""Using nominal kinematics."" ,True)
r.setFrame(p(0,0,0,0,0,0),-1,r""Fanuc M-20iA Base"" )
""Test the post with a basic program""
if Answer=="Normal":
    r.setDO(5, 1)#motor on// since fanuc starts from 1 and fanuc startrs from zero Do5 means
pin number 6 or A4
    for j in range(number_of_width):
        r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
        r.MoveL(p(X0+(j-1)*t,Y0-Pr,Z0,R0,P0,W0),[0,0,0,0,0,0],[0,0,0])# point 1
        r.setDO(7, 1)#feeding system on
        r.Pause(1000)
        r.setDO(7, 0)#feeding system off
        r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
        r.MoveL(p(X0+(j-1)*t,Y0,Z0,R0,P0,W0),[0,0,0,0,0,0],[0,0,0])# point 2
        r.setDO(1, 1)#compaction system on
        r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
        r.MoveL(p(X0+(j-1)*t,Y0+Y-T0,Z0,R0,P0,W0),[0,0,0,0,0,0],[0,0,0])# point 3
        r.setDO(3, 1)#cutting system on
        r.Pause(500)
        r.setDO(3, 0)#cutting system off
        r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
        r.MoveL(p(X0+(j-1)*t,Y0+Y,Z0,R0,P0,W0),[0,0,0,0,0,0],[0,0,0])# point 4
        r.setDO(1, 0)#compaction system off
        r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
        r.MoveL(p(X0+(j-1)*t,Y0+Iny,Z0+Inz,R0,P0,W0),[0,0,0,0,0,0],[0,0,0])# point 5
        r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
        #r.PROG = r.PROG_LIST.pop()
        print(j)# I have to delete it later on
    r.setDO(5, 0)#motor off
    r.setTool(p(0,0,0,0,0,0),-1,r""Set Tool"" )
    r.setTool(p(0,0,0,0,0,0),-1,r""Set Tool"" )
    r.MoveL(p(X0+(j-1)*F,Y0+Iny,Z0+Inz,R0,P0,W0),[0,0,0,0,0,0],[0,0,0])# end of path point
if Answer=="Fast Mode":
    for j in range(1,number_of_width,2):
        r.setDO(5, 1)#motor on
        r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
        r.MoveL(p(X0-(j-1)*t,Y0-Pr,Z0,R0,P0,W0),[0,0,0,0,0,0],[0,0,0])# point 1
        r.setDO(7, 1)#feeding system on
        r.Pause(1000)
        r.setDO(7, 0)#feeding system off
        r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
        r.MoveL(p(X0-(j-1)*t,Y0,Z0,R0,P0,W0),[0,0,0,0,0,0],[0,0,0])# point 2
        r.setDO(1, 1)#compaction system on
        r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
        r.MoveL(p(X0-(j-1)*t,Y0+Y-T0,Z0,R0,P0,W0),[0,0,0,0,0,0],[0,0,0])# point 3

```

```

r.setDO(3, 1)#cutting system on
r.Pause(500)
r.setDO(3, 0)#cutting system off
r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
r.MoveL(p(X0-(j-1)*t,Y0+Y,Z0,R0,P0,W0),[0,0,0,0,0,0],[0,0,0])# point 4
r.setDO(1, 0)#compaction system off
r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
r.MoveL(p(X0+X1-(j)*t,Y0+Y+Pr+Y1,Z0,R0+180,P0,W0),[0,0,0,0,0,0],[0,0,0])# point 5
r.setDO(7, 1)#feeding system on
r.Pause(1000)
r.setDO(7, 0)#feeding system off
r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
r.MoveL(p(X0+X1-(j)*t,Y0+Y+Y1,Z0,R0+180,P0,W0),[0,0,0,0,0,0],[0,0,0])# point 6
r.setDO(1, 1)#compaction system on
r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
r.MoveL(p(X0+X1-(j)*t,Y0+T0+Y1,Z0,R0+180,P0,W0),[0,0,0,0,0,0],[0,0,0])# point 7
r.setDO(3, 1)#cutting system on
r.Pause(500)
r.setDO(3, 0)#cutting system off
r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
r.MoveL(p(X0+X1-(j)*t,Y0+Y1,Z0,R0+180,P0,W0),[0,0,0,0,0,0],[0,0,0])# point 8
r.setDO(1, 0)#compaction system off
print(j)
r.setDO(5, 0)#motor off
r.setTool(p(0,0,0,0,0,0),-1,r""Set Tool"")
r.MoveL(p(X0+(j-1)*F,Y0+Iny,Z0+Inz,R0,P0,W0),[0,0,0,0,0,0],[0,0,0])# end of path point
r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
if Answer=="Test mode":
r.setDO(7, 1)#motor on
for j in range(1):
r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
r.setDO(6, 1)#feeding system on
r.Pause(2000)
r.setDO(6, 0)#feeding system off
r.MoveL(p(X0+(j-1)*t,Y0-Pr,Z0,R0,P0,W0),[0,0,0,0,0,0],[0,0,0])# point 1
r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
r.MoveL(p(X0+(j-1)*t,Y0,Z0,R0,P0,W0),[0,0,0,0,0,0],[0,0,0])# point 2
r.setDO(3, 1)#compaction system on
r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
r.MoveL(p(X0+(j-1)*t,Y0+Y-T0,Z0,R0,P0,W0),[0,0,0,0,0,0],[0,0,0])# point 3
r.setDO(1, 1)#cutting system on
r.Pause(500)
r.setDO(1, 0)#cutting system off
r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
r.MoveL(p(X0+(j-1)*t,Y0+Y,Z0,R0,P0,W0),[0,0,0,0,0,0],[0,0,0])# point 4
r.setDO(3, 0)#compaction system off
r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
r.MoveL(p(X0+(j-1)*t,Y0+Iny,Z0+Inz,R0,P0,W0),[0,0,0,0,0,0],[0,0,0])# point 5
r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
#r.PROG = r.PROG_LIST.pop()
print(j)# I have to delete it later on
r.setDO(7, 0)#motor off
r.setTool(p(0,0,0,0,0,0),-1,r""Set Tool"")
r.setTool(p(0,0,0,0,0,0),-1,r""Set Tool"")
r.MoveL(p(X0+(j-1)*F,Y0+Iny,Z0+Inz,R0,P0,W0),[0,0,0,0,0,0],[0,0,0])# end of path point
r.RunMessage("Program is done!")
#r.RunCode("TCP_On", True)# I don't know what is this
r.ProgFinish(r""PROGRAM_NAME"")
r.ProgSave(r""C:/Users/LPC/Desktop/Alireza
Saboukhi/CODEXXRESULT"",r""PROGRAM_NAME"",False,False)
print('it has been saved')
#r.PROG = r.PROG_LIST.pop()
input("Press Enter to close...")
r.ProgSendRobot("192.168.0.10", "/md:", "anonymous", "")
print('Congratulations! You can run the code now by Teach pendant')# I

```

Appendix F

```
# This file is used by your post processor (Fanuc_RJ3_DripFeed) and edition of Alireza Saboukhi for depositing in the tight corners
# to generate the appropriate file for your robot.
# You will find your robot program in the same folder where this file is located.
# To avoid showing this file after program generation you can select:
# Tools->Options->tab Other, then, uncheck "Show programs in Notepad"
```

```
import sys
import os
from datetime import datetime
import time
from tkinter import *
```

```
# datetime object containing current date and time
now = datetime.now()
# dd/mm/YY H:M:S
dt_string = now.strftime("%d/%m/%Y %H:%M:%S")

# Set up default parameters
PROGRAM_NAME = "sharp" # Name of the program
SPEED_RATE = 25 # Speed in mm/s of the welding path
ANGLE_VAL = 90 # Length of the surface
RADIUS_VAL = 10 # Width of the surface
def RunProgram():
    # Use default global variables
    global PROGRAM_NAME
    global SPEED_RATE
    global ANGLE_VAL
    global RADIUS_VAL
    # global APPROACH
    # global RADIUS
    # global SPEED_MOVE
    # global SIDES
    #global DRY_RUN
    # global RUN_MODE

# Create Instance Of Tkinter
# Generate the main window
app = Tk()
app.title("AFP application by Alireza Saboukhi")
Label(app, text="Hello, Please insert your desired values and name",
background="#34A2FE").pack()
entry_name = StringVar()
entry_name.set(PROGRAM_NAME)

entry_speed = StringVar()
entry_speed.set(str(SPEED_RATE))

entry_angle = StringVar()
entry_angle.set(str(ANGLE_VAL))

entry_radius = StringVar()
entry_radius.set(str(RADIUS_VAL))
#win.configure(background='#4D4D4D')
app.minsize(640, 400)
app.wm_iconbitmap('1552.ico')
#l1=Label(root, text="Program name")
Label(app, text="Program name").pack()
Entry(app, textvariable=entry_name).pack()
# Define a label and entry text for the speed
Label(app, text=" speed (mm/s)").pack()
Entry(app, textvariable=entry_speed).pack()
# Define a label and entry text for Angle
Label(app, text=" Desired Angle").pack()
Entry(app, textvariable=entry_angle).pack()
```

```

# Define a label and entry text for Radius
Label(app, text=" Desired Radius").pack()
Entry(app, textvariable=entry_radius).pack()
#####Start GUI
# Add a button and default action to execute the current choice of the user
def ExecuteChoice():
    #global DRY_RUN
    #global RUN_MODE
    global SPEED_RATE
    global PROGRAM_NAME
    global ANGLE_VAL
    global RADIUS_VAL
    #DRY_RUN = dryrun.get()
    #RUN_MODE = runmode.get()
    SPEED_RATE = float(entry_speed.get())
    PROGRAM_NAME = entry_name.get()
    ANGLE_VAL=float(entry_angle.get())
    RADIUS_VAL=float(entry_radius.get())
    # Run the main program once all the global variables have been set
    RunProgram()

Button(app, text='Generate', command=ExecuteChoice).pack()
Button(app, text='Done!', command=app.destroy).pack()
app.mainloop()
#####
sys.path.append(os.path.abspath(r""C:/RoboDK/Posts/"")) # temporarily add path to POSTS
folder

from Fanuc_RJ3_DripFeed import *

def p(x,y,z,r,p,w):
    a = r*math.pi/180.0
    b = p*math.pi/180.0
    c = w*math.pi/180.0
    ca = math.cos(a)
    sa = math.sin(a)
    cb = math.cos(b)
    sb = math.sin(b)
    cc = math.cos(c)
    sc = math.sin(c)
    return Mat([[cb*ca,ca*sc*sb-cc*sa,sc*sa+cc*ca*sb,x],[cb*sa,cc*ca+sc*sb*sa,cc*sb*sa-
ca*sc,y],[-sb,cb*sc,cc*cb,z],[0.0,0.0,0.0,1.0]])
#defining variables
X0=1490
Y0=-160
Z0=182.5
W0=180
P0=0
R0=90
Alpha=96
alpha1=43
alpha2=85
Y_DR=183
Y_DL=
YM=71+183
Y_LS=71+183+20
M=10
Y2=99.00
Z2=182.0
YC=105.42
ZC=217.27
YE=112.629
ZE=294.492

print('Total instructions: 5')
#RDK = Robolink()#initialize the ROBODK API
#RDK.setRunMode()
#robot=RDK.ItemUserPick("select a robot",ITEM_TYPE_ROBOT)
# tool=RDK.ItemUserPick("select a tool in robot",ITEM_TYPE_TOOL)
#robot.Connect()
#connected,message=robot.ConnectedState()

```

```

#print("connection status:")
# print(message)
r = RobotPost(r""Fanuc_RJ3_DripFeed"",r"" Fanuc M-20iA"",6,
axes_type=['R','R','R','R','R','R'], ip_com=r""192.168.0.10"", api_port=20500,
prog_ptr=419758960, robot_ptr=278881424)
#number_of_width=int(WIDTH_VAL/F)#bayad addad tabbei baashe

r.ProgStart(PROGRAM_NAME)
r.RunMessage(r""Program generated by Alireza Saboukhi for Fanuc M-20iA on "",True)
r.RunMessage(dt_string ,True)
r.RunMessage(r""Using RoboDK for depositing in the tight corners"",True)
r.setFrame(p(0,0,0,0,0),-1,r""Fanuc M-20iA Base"")
r.setTool(p(62,60,340,-15,0,0),-1,r""Set Tool"") # tool offset

r.setDO(7, 1)#collecting motor on
r.setDO(8, 1)#Peltier and Fan on
r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
r.MoveL(p(X0,Y0-Z0,Z0+100,R0,P0,W0),[0,0,0,0,0,0],[0,0,0])# point 0
r.setDO(6, 1)#feeding system on
r.Pause(2000)
r.setDO(6, 0)#feeding system off
r.MoveL(p(X0,Y0-Z0,Z0,R0,P0,W0),[0,0,0,0,0,0],[0,0,0])# point 1
r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
r.MoveL(p(X0,Y0,Z0,R0,P0,W0),[0,0,0,0,0,0],[0,0,0])# point 2
r.setDO(1, 1)#compaction system on
r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
r.MoveL(p(X0,Y0+Y_DR,Z0,R0,P0,W0),[0,0,0,0,0,0],[0,0,0])# point 3
r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
r.MoveL(p(X0,Y0+Y_DR,Z0,R0,P0-alpha1,W0),[0,0,0,0,0,0],[0,0,0])# rotation on point 3
r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
r.MoveL(p(X0,Y0+YM-Y_LS,Z0,R0,P0-alpha1,W0),[0,0,0,0,0,0],[0,0,0])# point 4 and end point of
the linear movement
r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
r.MoveC(p((X0,Y0+YM-Y_LS,Z0,R0,P0-alpha1,W0),[0,0,0,0,0,0],[0,0,0]),((X0,Y0+YM-
+M,Z+M,R0,P0-alpha1,W0),[0,0,0,0,0,0],[0,0,0]))((X0,Y0+YM+LS*sin(alpha-90),Z0+LS*cos(alpha-
90),R0,P0-alpha1,W0),[0,0,0,0,0,0],[0,0,0]))circular rotation between point 4 and 5
r.MoveL(p(X0,Y2,Z2,R0,P0-alpha1,W0),[0,0,0,0,0,0],[0,0,0])# point 6 and the next rotation
r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
r.MoveL(p(X0,Y2,Z2,R0,P0-alpha2,W0),[0,0,0,0,0,0],[0,0,0])# point 6 and the next rotation
r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
r.MoveL(p(X0,YC,ZC,R0,P0-alpha2,W0),[0,0,0,0,0,0],[0,0,0])# point 7 which is the cutting
point
r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
#r.setDO(3, 1)#cutting system on
#r.Pause(500)
#r.setDO(3, 0)#cutting system off
r.MoveL(p(X0,YE,ZE,R0,P0-alpha2,W0),[0,0,0,0,0,0],[0,0,0])# point 9 which is the end point
point
r.setSpeed(SPEED_RATE)# Set linear speed in mm/s
r.setDO(1, 0)#compaction system off
r.setDO(7, 0)#collecting motor off
r.MoveL(p(X0-50,Y0,Z0+50,R0,P0,W0),[0,0,0,0,0,0],[0,0,0])# point 1# end of path point
r.RunMessage("Program is done!")
#r.RunCode("TCP_On", True)# I don't know what is this
r.ProgFinish(r""PROGRAM_NAME"")
r.ProgSave(r""C:/Users/LPC/Desktop/Alireza
Saboukhi/aharpcorner"",r""PROGRAM_NAME"",False,False)
print('it has been saved')
#r.PROG = r.PROG_LIST.pop()
#for line in r.PROG:
# print(line)
#input("Press Enter to close...")
r.ProgSendRobot("192.168.0.10", "/md:", "anonymous", "")
print('Congratulations! You can run the code now by Teach pendant')# I have to delete it
later on

```