Automation of Process Planning for Automated Fiber Placement

Joshua A. Halbritter

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AUTOMATION OF PROCESS PLANNING
FOR AUTOMATED FIBER PLACEMENT

by

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ABSTRACT

Process planning represents an essential stage of the Automated Fiber Placement (AFP) workflow. It develops useful and efficient machine processes based upon the working material, composite design, and manufacturing resources. The current state of process planning requires a high degree of interaction from the process planner and could greatly benefit from increased automation. Therefore, a list of key steps and functions are created to identify the more difficult and time-consuming phases of process planning. Additionally, a set of metrics must exist by which to evaluate the effectiveness of the manufactured laminate from the machine code created during the Process Planning stage.

This work begins with a ranking process which was performed through a survey of the Advanced Composites Consortium (ACC) Collaborative Research Team (CRT). Members were interviewed who possessed practical process planning experience in the composites industry. The Process Planning survey collected general input on the overall importance and time requirements for each function and which functions would benefit most greatly from semi-automation or full automation. Layup strategies, in addition to dog ears, stagger shifts, steering constraints, and starting points, represented the group of functions labeled as process optimization and ranked the highest in terms of priority for automation. The laminates resulting from the selected parameters are evaluated through the occurrences of principal defect metrics such as fiber gaps, overlaps, angle deviation and steering violations.
This document presents an automated software solution to the layup strategy and starting point selection phase of Process Planning. A series of ply scenarios are generated with variations of these ply parameters and evaluated according to a set of metrics entered by the Process Planner. These metrics are generated through use of the Analytical Hierarchy Process (AHP), where relative importance between each of the fiber features are defined. The ply scenarios are selected which reduce the overall fiber feature scores based on the defects the Process Planner wishes to minimize.
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<tr>
<td>ACC</td>
<td>Advanced Composites Consortium</td>
</tr>
<tr>
<td>AESP</td>
<td>Association of Energy Services Professionals</td>
</tr>
<tr>
<td>AFP</td>
<td>Automated Fiber Placement</td>
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<tr>
<td>AHP</td>
<td>Analytical Hierarchy Process</td>
</tr>
<tr>
<td>AHS</td>
<td>American Helicopter Society</td>
</tr>
<tr>
<td>AIAA</td>
<td>American Institute of Aeronautics and Astronautics</td>
</tr>
<tr>
<td>ALM</td>
<td>Additive Layer Manufacturing</td>
</tr>
<tr>
<td>ASCE</td>
<td>American Society of Civil Engineers</td>
</tr>
<tr>
<td>ASME</td>
<td>American Society of Mechanical Engineers</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
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<tr>
<td>CAPP</td>
<td>Computer Aided Process Planning</td>
</tr>
<tr>
<td>CRT</td>
<td>Collaborative Research Team</td>
</tr>
<tr>
<td>FAA</td>
<td>Federal Aviation Administration</td>
</tr>
<tr>
<td>FOD</td>
<td>Foreign Object Debris</td>
</tr>
<tr>
<td>ICPS</td>
<td>Ingersoll Composites Programming Software</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NURBS</td>
<td>Non-uniform rational B-spline</td>
</tr>
<tr>
<td>SAE</td>
<td>Society of Automotive Engineers</td>
</tr>
<tr>
<td>SAMPE</td>
<td>Society for the Advancement of Material and Process Engineering</td>
</tr>
<tr>
<td>VCP</td>
<td>VERICUT Composite Programming</td>
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1.1 BACKGROUND

Automated Fiber Placement (AFP) is increasingly utilized for manufacturing composite materials into useful parts [1]. An AFP machine is typically comprised of a robotic arm/gantry and a fiber placement head that can layup multiple strips of primarily carbon fiber reinforced polymer-matrix material. These strips of carbon fiber material, known as tows, are often laid up in differently oriented layers, known as plies, to increase the strength and isotropy of the part [2]. To secure adhesion of these tows, the fiber placement head must have a method of heating the resin and compacting it down to the surface. This is accomplished by using a controlled amount of heat and compaction load supplied by the AFP end-effector [3]. After placing the first ply to the tool, subsequent plies can be added until the desired shape and strength of the part has been achieved.

AFP brings a more efficient and productive method of composite manufacturing; however, the automated manufacturing process is far from optimized, and defects can persist throughout the products created with AFP manufacturing. The defects found in the layup portion of the AFP process are often an unintended part of the layup process and forced by the nature of the geometrical shape. Therefore, it is critical to understand what these defects are and how they interact with the part. Tow gaps/overlaps and wrinkles represent some of the most common defects for composite parts. These defects have been investigated in previous work. For example, tow gaps/overlaps, have been found to result
in reduction in laminate strength in the work by [4]. Additionally, it has been shown that gap/overlap defects lead to a decrease in strength at the site of the defect, whereas an overlap is shown to increase the strength at that site in a constant stiffness laminate [4] [5]. The geometric effect of these defects and their potential consequence, such as strength reduction, were detailed in [6]. It has also been determined that gaps and overlaps can lead to resin-rich and fiber-rich areas in the part is left untreated [7]. The wrinkle defect has also been investigated. The effects of minimum turning radius on tow-wrinkling were presented in [8]. Another paper detailed the reduction in strength that resulted from wrinkling and identified it to be as high as 36% [9]. Finally, the detrimental effects of the defects on the final laminate’s structural properties are included [10] [11].

1.2 PROCESS PLANNING

Since AFP is an automated process, it is necessary to create numerical control (NC) code which defines the creation of the laminate part. The development of this NC code is known as process planning, which creates an AFP manufacturing plan based on the working material, composite design, and manufacturing resources. Process planning (Figure 1.1) represents one of the most critical and user-interactive portions of the AFP process. In this step, a process planner will use a multitude of different functions to prepare the design for layup by the machine. To use these functions, a process planner must use his knowledge of the part being made, the tool being laid up on, and the machine.

The economic impacts of process planning for AFP arise from the reduction in time it takes to program the machine prior to manufacturing by embedding design for manufacturing concepts well ahead in the product lifecycle. It also reduces the labor and material cost that may result during manufacturing due to poor and/or inefficient
Therefore, improving process planning will allow for more cost efficient and faster manufacturing using AFP, leading to faster certification cycles. To improve AFP process planning, the functions that make up the process planning stage must first be identified and discretized. By defining these individual functions, their total contribution to the result can be interpreted and steps can be taken to automate the most important and time-consuming functions.

![Process planning flow chart](image)

**Figure 1.1 Process planning flow chart**

### 1.3 THESIS OUTLINE

This thesis is organized as follows to develop an understanding of the overall process planning process, and how to begin to quantify laminates regarding their fiber defects.

Chapter 2 presents a literature review of common layup strategies and provides the mathematical and geometrical basis that are used. The aspects of initiation, propagation and surface representations are discussed, in addition to the different types of geometry that each layup strategy is best suited for.
Chapter 3 discusses the various fiber defects that are commonly observed in AFP. The defects are defined and depicted through images. Additionally, the different aspects of the defects are discussed, including their anticipation, existence and significance. Where anticipation discusses the predictability of the defect, existence covers the techniques available for detecting the defect, and significance discusses the potential impacts of the defect on the resulting laminate.

Chapter 4 develops the understanding of the process planning steps that occur during the AFP design phase. Process planning itself is broken down into a set of discrete functions that gathers information from several streams in order to create a coherent build plan. This chapter discusses how information flows between these functions, and how the functions utilize that information. Additionally, a survey is presented which helped to rank and categorize these functions into logical groupings.

Chapter 5 sets forth a set of methods for quantifying fiber defects into categorize of instances and severity. Additionally, a prioritization process for different families of defects is defined, which allows for a user specific weighting for each defect to be used. Finally, an objective function for quantifying ply scenarios with these concepts of defects and prioritization is defined.

Chapter 6 is an extension of chapter 5 and describes the implementation of computer aided process planning into the CAPP module.

Chapter 7 concludes the presented work with recommendations and present future research opportunities.
CHAPTER 2
LITERATURE REVIEW

This chapter provides background on the concept of path planning for AFP. The primary goal of path planning is to develop a series motion paths along a tool surface which when followed will create the desired laminate structure. These motion paths are typically constrained by a set of ply boundaries which define the extent of the material placement, and a ply angle which defines the orientation of the material within the ply boundary. Additionally, several defects can arise due to the interaction of the tool surface and the material system (Chapter 3), and it is desirable to limit their existence by proper selection of layup strategy parameters. The follow sections of Chapter 2 discuss a variety of layup strategies and compares their benefits and drawbacks for different tool geometries.

2.1 LAYUP STRATEGY CONCEPTS

This section covers the various concepts regarding the geometry of fiber paths that can be utilized to generate surface coverage. These geometrical concepts define the interaction of the thin and stiff material of the fiber tows being placed on a potentially complex geometrical tool surface.

2.1.1 Direction of The Fiber

The different courses laid up by the AFP process need to be placed in a way that the fibers orientations meet the required design specifications. Often, plies are manufactured with fibers having well-defined angles such as 0°, 90°, 45°, -45° as they
provide a quasi-isotropic behavior for the structure [12]. Typically, the 0° angle direction follows the longest dimensions of the surface as in Figure 2.1. It is straight-forward to lay up plies with these angles on a flat panel (Figure 2.1) however on complex surfaces, it is more difficult as the fiber angles in the tow can change due to the geometry of the surface. Therefore, each layup strategy will produce its own uniquely oriented laminates as the tooling surface changes. This chapter details all the layup strategies found in the literature on the AFP process. This will allow the right strategy to be chosen for the tooling to obtain a proper structure.

![Flat panel with different layup fiber angles](image)

Figure 2.1 Flat panel with different layup fiber angles

2.1.2 Minimum Turning Radius

Another condition to check before finalizing the path design is the turning radius or the curvature of the path. Since the tows used in the AFP process have a finite width, the edges of the tow will be either under tension or compression while trying to adhere a rectangular shaped tow to a curved path. This mismatch in length between the tow and the actual path on the surface will push the excess material to buckle out-of-plane to form a
pucker or wrinkle (Figure 2.2) on the compressive edge of the tow. As for the tensile side, the shortage of material will push the fibers to move closer to the center line leading to tow straightening, or in the severe cases to move out-of-plane and fold over.

To avoid these defects (defined in Chapter 3), a minimum steering radius must be set beforehand, depending on the material used. The minimum steering radius can be determined experimentally by trying different radii of curvature with different combination of process parameters (speed, temperature, roller pressure).

![Figure 2.2 Most common tow steering defect [1]](image)

2.1.3 Reference Curves

In order to propagate fiber paths across the tool surface, an initial (or reference) curve is needed. In this section, the different strategies to determine the reference curve will be detailed. The literature describes both parametric approaches and the use of a meshes. A mesh provides useful information, such as the different areas of the facets and their normal, which are important to generate the toolpath along the course. Nevertheless, a mesh approximates the surface, so the precision obtained depends on the accuracy of the mesh. However, a more refined mesh increases the computation time. Using a parametric
approach, the surface would be known more precisely. In this section and the following ones, the different strategies to find reference curves are detailed.

2.1.4 Constant Curvature

For a flat plate, a constant curvature path is an arc of circle, with a possible parametrization as defined by equation 2.1, where, \((x_0, y_0)\) are the coordinates of the center, and \(1/\kappa\) is the radius of curvature. Constant curvature paths are frequently used as trials to determine the critical radius at which wrinkling will occur for a given set of process parameters.

\[
\begin{align*}
  x(t) &= x_0 + \frac{1}{\kappa} \cos t \\
  y(t) &= y_0 + \frac{1}{\kappa} \sin t
\end{align*}
\]

\[(2.1)\]

\[
\sin \varphi(x) = \frac{r_0 \sin T_0}{r(x)} + \frac{\kappa}{\sin \alpha} \left( \frac{r(x)^2 - r_0^2}{2r(x)} \right)
\]

\[(2.2)\]

\[
\kappa = \left( \frac{r_1}{\bar{r}} \sin T_1 - \frac{r_0}{\bar{r}} \sin T_0 \right) \frac{1}{L} \cdot \left[ \bar{r} = \frac{r_0 + r_1}{2} \right]
\]

\[(2.3)\]

For the special case of the cone (Figure 2.3) presented in [13], [14], [15], it is possible to obtain a closed form solution for a reference curve with a constant curvature. The equation of the curvature \(\kappa\) and the local fiber orientation \(\varphi\) as a function of the position on the surface is therefore given by equation 2.2 and 2.3.

Where: \(r_0, r_1\) and \(\alpha\) are the small, the larger radii and the cone angle; \(r(x)\) represents the perpendicular distance from the revolution axis to a point on the shell and varies linearly for this shell configuration: \(r(x) = r_0 + x \sin \alpha\); \(L\) is the length along the surface; \(T_0\) and \(T_1\) are respectively the fiber orientation at the small and the big radius of the cone. Then the curvature \(\kappa\) is kept constant along the surface to obtain the reference curve (Figure 2.6)
The case of a beam and a cylinder is studied respectively in [16] and [17] using the same method. The case of a planar surface is developed in [18] and [19] where the fiber angles follow a constant curvature path from a boundary to the center of the surface.

For a general surface, the following system of 2\textsuperscript{nd} order differential equations in terms of the surface parameters $u$ and $v$ must be solved numerically with a prescribed geodesic curvature $k_g$, to obtain a constant curvature path:

\begin{align*}
    &u'' + \Gamma_{11}^1 u'' + 2\Gamma_{12}^1 u' v' + \Gamma_{22}^1 v'' = \frac{k_g(E u' + G v')\sqrt{Eu'^2 + 2Eu'v' + Gv'^2}}{\sqrt{E - F^2}} \\
    &v'' + \Gamma_{11}^2 u'' + 2\Gamma_{12}^2 u' v' + \Gamma_{22}^2 v'' = \frac{-k_g(E u' + F v')\sqrt{Eu'^2 + 2Eu'v' + Gv'^2}}{\sqrt{E - F^2}}
\end{align*}

\[2.4\]

Figure 2.3 Cone geometry [13], [14], [15]

The inconvenience of this strategy is that the fiber directions are not always respected.
Another strategy which specifies a reference curve with a constant curvature on a flat panel is presented by [20]. This strategy uses the variation of the fiber angle between two points, each one having a different fiber angle $T_0$ and $T_1$ separated by a distance $d$. $T_0$ defines the starting point of this path. Between $T_0$ and $T_1$, a constant curvature arc with radius $R^*$ is defined (Figure 2.4).

A polynomial approach can be taken to find the reference curve, using a mesh description [21]. The method requires that the surface equation in the x-y system (or a polar system) is known. Assuming that the path function is $z = f(x,y)$, one can deduce the fiber angle $\theta$ in each finite element center.

$$\theta(x,y) = \begin{cases} \tan^{-1}\left(-\frac{a_1 + a_3y + 2a_4x}{a_2 + a_3x + 2a_4y}\right), & a_2 + a_3x + 2a_4y \neq 0 \\ \frac{\pi}{2}, & a_2 + a_3x + 2a_4y = 0 \end{cases} \quad (2.5)$$

In this method, the fiber angle is constant in a finite element so that the reference curve can then be defined. Having $a_1$, $a_2$, and $a_3$ equal to zero, a constant curvature path can be defined as in Figure 2.5.
2.1.5 Geodesic Guide Curves

The geodesic path can also be known as the natural path. A geodesic is the shortest path between two points along a three-dimensional surface in Cartesian space [22]. This is why the geodesic path is a straight line on a flat panel [20].

Also, a geodesic path can be obtained by specifying a starting point and a direction of travel. For a general parametric surface, a geodesic path must satisfy the following system of differential equations:

\[
\begin{align*}
    u'' + \Gamma_{11}^1 u'^2 + 2\Gamma_{12}^1 u'v' + \Gamma_{22}^1 v'^2 &= 0 \\
    v'' + \Gamma_{11}^2 u'^2 + 2\Gamma_{12}^2 u'v' + \Gamma_{22}^2 v'^2 &= 0
\end{align*}
\] (2.6)

which can be obtained from 2.4 by setting the geodesic curvature to zero. In order to solve this system of equations, four initial conditions have to be set: \(u(0) = u_0, v(0) = v_0\), \(u(1) = u_1, v(1) = v_1\) for the geodesic path between two points \(P_0 = S(u_0, v_0)\) and \(P_1 = S(u_1, v_1)\), or \(u(0) = u_0, v(0) = v_0, u'(0) = u'_0, v'(0) = v'_0\) for the geodesic path starting at \(P_0 = S(u_0, v_0)\) with a direction \((u'_0, v'_0)\).

For the case of a flat surface, the system of equations in 2.6 can be simplified to obtain the parametric equation of a straight line which is the shortest path between two points.
For example, [13], [14] [15] define a geodesic path on a cone. It can be done from the equations of the conical surface as the geodesic path has a curvature $\kappa$ equal to zero in the equation 2.2 and 2.3 (Figure 2.6).

In [23], a layup strategy algorithm is developed to fit a Y shape. Starting from one branch of the Y surface, and given an initial fiber angle, a geodesic path is defined. However, once at the junction of the Y, the geodesic path might change or won't be able to propagate on the surface. The different given solutions to continue the path are to go in the direction of the minimum curvature, to try to reach a geodesic path on the other branch of the Y (Figure 2.7), or to create a straight path on the other branch respecting the steering conditions for the courses.

2.1.6 Fixed Angle Reference Curve

For a fixed angle strategy, the fiber angle in the reference curve is constant all along the surface. First, a constant angle reference curve is calculated using a mesh approach is
given. Then the process of finding the reference curve using a parametric approach will be developed.

![Reference curve on a Y surface](image)

**Figure 2.7 Reference curve on a Y surface [23]**

### 2.1.6.1 Using a mesh

The method presented in [24] uses the mesh information contained in a STL file. After a preliminary computation to perform initial topology reconstruction a functional model including the vectors/edges, the nodes, the facets, and the normal vectors of the facets is generated. If one uses another mesh file type, this information needs to be first generated to use this method. For instance, to find the normal vectors from the vertices of a triangular mesh a method is provided in [25].

Using this information, a first slicing algorithm creates the reference curve. Basically, a tangent plane in one direction is used to find all the points on the mesh which intersect this plane (Figure 2.8). To do so, a first point, \( P_1 \), of a triangle which intersects the plane and the edge is found. Then, using the structure reconstruction, the mesh triangle in which this point belongs is already known. Finally, the second point, \( P_2 \), of the triangle mesh intersecting the plane is found and one can move forward to the next triangle that this last point belongs to. This loop continues until the tangent plane no longer intersects the
surface anymore. The fact that the direction of the tangent plane used is constant results in the fiber angle constant along the surface.

![Diagram](image)

Figure 2.8 Fix angle reference curve using a mesh [24]

To find another fix angle path, the meshed plane is rotated by a constant angle from the previous path defined before. In Figure 2.9, the rotation around the z-axis of the triangle D₀D₁D₂ by an angle of 45° results in a new triangle D₀₀D₁₁D₂₂. In this diagram, the reference curve is v and P₀P₁ is the offset of this reference curve at a fixed angle of 45°.

![Diagram](image)

Figure 2.9 Constant angle method [24]

2.1.6.ii Parametric approach

As previously stated, the parametric approach is more dominant in the literature. The method in [21] explained in the previous section can also be used to determine a fixed angle reference curve on a flat panel. With a₁ = a₂ = 1 and a₃ = a₄ = a₅ = 0 in 2.5 the reference curve presented in Figure 2.10 is obtained.
In [26], [27] [28] [29] [30] [31] a major axis is projected on the surface $S(u,v) = [x(u,v), y(u,v), z(u,v)]$. This projection gives an intersection line on the surface. The major axis plane equation is $P(x,y,z) = ax + by + cz + d = 0$. Hence, the surface plane intersection equation is:

$$f(u, v) = ax(u, v) + by(u, v) + cz(u, v) + d = 0$$  \hspace{1cm} (2.7)

Discrete points are needed to find the offset curves to cover the surface, therefore points on this intersection line need to be determined. A starting point is needed from which the reference curve will be propagated. This starting point is found on a boundary using a bracket method followed by a Newton-Range method (NRM) on 2.7 to find the intersection point between the boundary and the projection of the major axis. To find the next point of the reference curve, one step is done in one direction (length of the step is defined) then the other step uses the NRM to converge to the surface-plane intersection line. The propagation is done until the major axis doesn't intersect with the surface anymore (Figure 2.11).
[30] uses the same method to find the reference curve but the compaction roller position is also considered. On every point of the reference curve, a tangent plane to the surface is inserted. The center of the roller is then placed on the normal to the surface calculated at each of the points (Figure 2.12), thus, determining the roller path location following the reference curve allows, on very complex surfaces, to avoid defects therefore increasing the layup efficiency.

In [23], [32], an iterative algorithm is developed using a defined reference direction. Beginning from a point $P_i$, a tangent vector $d$ of the surface is created, that follows the direction of the reference curve. Another vector $t$ is created by rotating $d$ around the normal vector by a defined placement angle $\phi$. Finally, a point $P_F$ is defined on this vector $t$ at a...
certain distance from Pi and is projected on the surface which gives a point \( P_{i+1} \) on the surface (Figure 2.13). The process is iterated until the path reaches a boundary.

![Reference curve using an iterative algorithm](image)

Figure 2.13 Reference curve using an iterative algorithm [23]

Finally, [13], [14] [15] determined a reference curve for a conical shape (Figure 2.6). It is a good example where the parametric approach is faster and more efficient than using a mesh due to the simplicity of the conical parametric surface. A resolution of equations 2.2 and 2.3 that keep the fiber angle constant gives the reference curve on the cone surface with a fixed angle.

However, as these methods only focused on the fiber angle, it is possible to result in tow-steering too severe at some points of the reference curve, which makes the manufacturing process difficult if not impossible. This is one of the main reasons why layup strategies need to include manufacturing configurations to generate optimal toolpaths.

2.1.7 Variable angle guide curves

The fiber orientation can vary along the reference curve. This is in contradiction with the statements in Section 2.1.1, as the fiber directions are not constant anymore. This variation of the fiber direction leads to a variable-stiffness [33]. The higher degree of freedom for the reference curve allows the creation of structures which account for non-unidirectional constraints. Therefore, the calculations and the optimization are harder. In
this section, different strategies to define the reference curve with variable angle fibers will be explained.

2.1.7.i Linear variation

A variable fiber angle layup strategy is based on the linear variation of the fiber directions in the path. This method has been used extensively in the literature, including: [14] [15] [16] [20] [21] [34] [35] [36], [37] [38] [39], [40] [41] [42] [43] [44] [45], [46].

This strategy lies in the linear variation of the fiber angle between two points, each one having a different fiber angle $T_0$ and $T_1$ separated by a distance $d$. $T_0$ defines the starting point of this path. The axis system of fiber orientation is defined by rotating the rosette by an angle $\phi$. This new axis defines a new fiber orientation called $r$. The fiber path is then defined by $\phi < T_0 | T_1 >$ and varies linearly along $r$ from $T_0$ to $T_1$ (Figure 2.14).

![Figure 2.14 Reference curve with a linear variation [37], [47]](image)

According to Figure 2.14, one can calculate $\theta(r)$ the fiber angle as a function of $r$ in the polar coordinate:

$$\theta(r) = \begin{cases} \phi + (T_0 - T_1) \cdot \frac{r}{d} + T_0, & -d \leq r \leq 0 \\ \phi + (T_1 - T_0) \cdot \frac{r}{d} + T_0, & 0 \leq r \leq d \end{cases}$$

(2.8)
The reference curve repeats indefinitely with a 2d period until it reaches a boundary.

2.1.7.ii  Nonlinear variation
Non-linear angle variations have been employed to obtain higher structural performance [45]. Different methods have been used to define the layup trajectories with this non-linear variation and are explained in this section.

2.1.7.iii  Free form
First, B-spline curves have been used to define a parametric equation for reference curves. However, this method has its limits as larger amounts of control points reduce its effectiveness. This results in low-resolution path with bad connectivity between the control points [48].

A Bezier curve, frequently used in computer graphics to model a smooth curve, is another way to define the reference curve with a parametric equation of the path on the surface using a set of control points [49]. In [50], the Bezier curve is represented with a vector equation including the control points and the junction angles between each point. An example of this equation for a Bezier curve between two control points is given below:

\[ \vec{B}(t) = (1 - t)^2 \vec{P}_0 + 2(1 - t)t \vec{Q}_1 + t^2 \vec{P}_2, \quad t \in [0,1] \]  
\[ \vec{P}_0 = (0,0), \quad \vec{Q}_1 = (\beta_1 a, \beta_1 a \tan \alpha_0), \quad \vec{P}_1 = (a, \beta_1 a \tan \alpha_0 + (1 - \beta_1)a \tan \alpha_1) \]

Where \( \vec{P}_0 \) is the starting point, \( \vec{P}_1 \) is the end point and \( \vec{Q}_1 \) is the junction between the two of them; The angles \( \alpha_0 \) and \( \alpha_1 \) are defined as in Figure 2.15 and \( \beta_1 \) is the angle variation coefficient which defines the location of the junction point \( \vec{Q}_1 \).
Figure 2.15 Tow path represented by piecewise quadratic Bezier curves with two control points [50]

One can then deduce the coordinates of any point on the curve:

\[ x = (1 - 2\beta_1)t^2 + 2\beta_1 t, \quad 0 \leq x, t \leq 1 \]  

\[ y = \left( (1 - \beta_1)\tan \alpha_1 - \beta_1\tan \alpha_0 \right)t^2 + 2\beta_1 \tan \alpha_0 t \]  

(2.11)  

(2.12)

It is also possible to add other segments to increase the freedom of the tow path. To do so, a new parameter needs to be introduced which makes the link between the different junction points:

\[ \gamma = (i - 1 + \beta_i)/N, \]

Where i and N are respectively the current segment number and the total number of segments. An example of a tow path between two segments is given in Figure 2.16.

Figure 2.16 Tow path represented by piecewise quadratic Bezier curves [50]
In [33], the surface is considered as a bicubic Bezier surface with 16 control points as design perimeters. The control points are forming a mesh and the fiber angle can be written in a cubic polynomial form:

\[ sr = ar^3 + br^2 + cr + d \] and \[ r = x_m \cos \alpha + y_m \sin \alpha \]

As the fiber angle is constant in a finite element and considering the point \( M(x_m, y_m) \) the center of the finite element, the fiber angle within a finite element is:

\[ \theta = \tan^{-1}\left[3a(x_m \cos \alpha + y_m \sin \alpha)^2 + 2b(x_m \cos \alpha + y_m \sin \alpha) + c\right] + \alpha \]

Figure 2.17 Reference curve optimizing the compliance constraints [51]

In [51], the reference curve trajectory is optimized following different control points. Indeed, control points are defined on the surface and the fiber angle varies until the compliance is minimized (Figure 2.17). The optimization problems are resolved due to finite difference sensitivities. The curvature of the surface can also be considered in the optimization to decrease the compliance.
2.1.7.iv  Polynomial

Multiple research groups, including [46] [52] [53] [54], utilize a mesh and a cubic polynomial function to determine the fiber angle along the surface:

\[ f(x, y) = c_{00} + c_{10}x + c_{01}y + c_{20}x^2 + c_{11}xy + c_{02}y^2 + c_{30}x^3 + c_{21}x^2y + c_{12}xy^2 + c_{03}y^3 \]  \hspace{1cm} (2.15)

The different coefficient of the polynomial function can vary with the surface as they determine the surface shape. The fiber angle \( \theta \) is constant within a finite element (but can vary from one finite element to another) so it is calculated in the center of the finite element \((x_C, y_C)\):

\[ \theta(x_C, y_C) = \tan^{-1}\left(\frac{\partial f / \partial x}{\partial f / \partial y}\right), \text{ when } \partial f / \partial y = 0, \theta = 90^\circ \]  \hspace{1cm} (2.16)

The method used is more efficient than the ones using spline functions [48]. The fiber shape is defined in the polynomial functions while, using spline functions, simultaneous equations need to be solved for the same task. The path is then optimized by the genetic algorithm defined in the following section.

In [55], Lagrangian polynomial functions are used to determine the reference curve. The following equation gives the expression of the fiber angle on the surface:

\[ \theta(x, y) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} T_{mn} \cdot \prod_{m \neq 1} \frac{x - x_i}{x_m x_i} \cdot \prod_{n \neq j} \frac{y - y_j}{y_n - y_j} \]  \hspace{1cm} (2.17)

Where \((x_i, y_j), (x_m, y_n)\) are the x-y coordinates of reference points. The reference curve is then obtained by resolving the equation at different reference points (Figure 2.18).
2.2 COVERAGE STRATEGIES

In this section, the different coverage strategies are detailed. Indeed, three strategies can be used to cover the entire surface. The first one computes the different curves independently and the two others compute all the other course paths from a reference curve.

2.2.1 Offset Curves

The offset curves, or parallel curves strategy, is the most common for path planning. Adjacent curves on the surface are computed from the reference curve to achieve total coverage. Towpaths within a course must be determined using this method due to the roller mechanism that ensures all tows within a course are parallel. To explain this coverage strategy, the distinction between the parametric approach and the usage of a mesh are investigated.
2.2.1.i Parametric approach

To compute the parallel curves parametrically, a closed form solution for continuous planar curves exists by taking equidistant points following the normal vector along the curve. This can be expressed as:

\[
C(t) : \begin{cases} 
    x(t) = u_c(t) \\
    y(t) = v_c(t) \\
    z(t) = 0 
\end{cases} \quad C_p(t) : \begin{cases} 
    x_p(t) = u_c(t) - d \frac{v_c'(t)}{\left(u_c'^2(t) + v_c'^2(t)\right)^{1/2}} \\
    y_p(t) = v_c(t) + d \frac{u_c'(t)}{\left(u_c'^2(t) + v_c'^2(t)\right)^{1/2}} \\
    z_p(t) = 0 
\end{cases}, \quad (2.18)
\]

where \(C(t)\) is the reference curve and \(C_p(t)\) is a parallel curve at a distance \(d\) from the original, and \(d\) is either a positive or a negative number.

For a general surface, a closed form solution for the parallel curves does not exist in most cases. Hence several algorithms [27], [29], [30] have been developed to compute offset/parallel curves numerically.

For instance, a similar approach is used in [27] for the planar case to find parallel curves by following the vector normal to the reference curve. This vector designated \(O\) (Figure 2.19) can be found by taking the cross product between the tangent vector to the curve and the normal vector to the surface. Then at a distance \(d\) along the vector \(O\), a point \(P'\) is projected to the surface following the normal vector using a Global Closest Technique. This process is repeated at every point-step along the curve to obtain the new parallel curve. The resulting error from using this technique 2.19) is reported to be [27]:

\[
Error = d \left( 1 - \frac{\psi}{\tan \psi} \right) \tag{2.19}
\]

Therefore, the error increases by taking a further offset curve (in the case of wider courses), and in the case of highly curved surface.
A more accurate method is presented in [27], [29], [30], [31] by taking the intersection between the plane perpendicular to the curve and the mold surface. To do so, a numerical approach presented in [56] is used to determine the resulting curve. Then, the offset point can be found by taking the required distance along the perpendicular arc. If the reference path is shorter than the offset path which does not reach a boundary, a last step is needed to obtain a complete offset path. In this case, the offset curve is completed by interpolating the last point from the calculated ones until it reaches the boundary.
Three other methods are presented in [57] to compute parallel curves on a NURBS surface. The first method commonly referred to as “section curves” is similar to the ones presented in [27] [29] [30] [31]. The other two methods consist of generating orthogonal curves to the reference by either taking vector-field curves or geodesic curves. Once the orthogonal curve is defined in either of these methods, the offset points can be calculated at the required distance from the reference curve. The new parallel curve is then obtained by interpolating these points.

The advantage of computing parallel curves is that the offset curves are equidistant so there are no gaps or overlaps between the paths or the courses during the layup process. However, considering a complex surface, the fibers directions in the offset curve can change.

To optimize the fiber direction and to avoid significant deviation of these angles, [58] considers an interval of direction and tests the deviation of the offset fibers while the fiber direction in the reference path varies. The reference curve which conserves the most fiber directions in the offset path constant is then selected.

2.2.1.ii  Mesh: Fast Marching Method
This method has been introduced by [51] [59] and is based on the Eikonal equation, with a depiction of the results in Figure 2.21. This equation is mostly used in optic and is used to calculate the propagation of a wave with a particular speed. Hence one can calculate the different position of this wave at every time once it starts propagating.

The fast-marching methods starts from a random reference curve on the surface. First, the reference curve needs to be discretized. The intersection points between the mesh and the reference curve form the discretized reference path. For initialization, all these
Figure 2.21 Steps of the Fast Marching Method to offset a reference curve [59]

points have a time value of 0. Then, the reference curve is propagated at a defined speed so every node of the mesh will hit the propagated curve at a certain time. Moreover, knowing the time value of two nodes of one mesh triangle, it is possible to calculate the time value of the last node. On an accurate triangular mesh Figure 2.22, knowing the time values of the points A and B respectively $T_A$ and $T_B$, one can find the time value of $T_C$.

![Diagram of Fast Marching Method](image)

**Figure 2.22 Finding $T_C$ knowing $T_A$ and $T_B$ [59]**

Using the following equations and with $1/f$ the propagation speed of the reference curve:

$$
\frac{(T_B - T_A)}{f} = \frac{h}{BC \sin(\beta - \theta)}
$$

$$
T_C = T_B + \frac{h}{BC \sin(\beta - \theta)}
$$
One can calculate $T_c$:

$$T_c = h.f + T_B$$  \hfill (2.22)

To propagate this calculation, the Fast Marching Method explained in [60] is used. This method looks for the neighbor nodes of the one with the lowest time value. Then, all the nodes around this one are updated. The initial node won’t be considered anymore, and the update is done from the next node with the lowest value. It is important to notice that the time value of each node is updated only if the calculated value is smaller than the previous one.

Once all the nodes’ time values are known, for each time value an offset curve of the reference curve is drawn. Knowing the speed and time, an offset curve with the proper distance from the reference curve can be found. The offset curve joins the different iso-value points.

Figure 2.23 Difference between a non-extended and an extended reference curve [59]
However, to obtain a real parallel curve, the reference curve must be considered as infinite (meaning that it goes through the boundaries) when propagated with the Fast Marching Method. Indeed, if the reference path is not extended, the offset curves won’t necessarily be parallel to it at every point (Figure 2.23)

2.2.2 Shifted Curves

In [13] [17] [18] [20] [34] [35] [36] [37] [38] [39] [61], the reference curve is simply shifted along its perpendicular direction on the surface by applying a translation. The advantage of this method is its simplicity, however, on a complex surface, the fiber directions of the offset path are not guaranteed, and the presence of gaps and overlaps is possible.

![Figure 2.24 Tow path Definition: (a) Parallel method; (b) Shifting method [62]](image)

![Figure 2.25 Gap and Overlap resulted in the shifting method [62]](image)

2.2.3 Independent Curves

Another approach to cover the entire surface is to draw the different curves independently. Regarding complex surfaces, independent curves can be a solution to limit extreme steering. To cover the surface, it is possible to draw the courses staggered one to another with a constant length and with a different direction [27]. If the surface is complex, the different courses are not necessarily parallel to each other if the required direction is maintained. This will induce gaps and overlaps as seen in Figure 2.26.
Another strategy based on the principle of independent fibers creates many short courses, where the short courses help control the presence of gaps and overlaps. This strategy has been studied by [28] for a conical surface Figure 2.27. The drawback of this method is that the short independent courses reduce the resulting laminate’s strength due to the many discontinuous fibers throughout the structure.

Figure 2.27 Succession of short independent courses to cover a conical surface [28]

2.3 CONCLUSION

This chapter provided a literature review of the of the various layup strategies as they exist in literature. Important concepts that were covered include initiation and propagation of surface coverage. Initiation was commonly performed through the use of a single starting point combined with a desired fiber orientation, or with the use of a specified guide curve. The propagation methods had several variations, and would either strictly
follow previous fiber paths, loosely follow previous paths, or be completely independent and strictly based on surface geometry. Additionally, strategies would either require complete surface definitions in the form of parametric surface data or could be computed on meshed surface representations. With these three concepts of initiation, propagation and surface representation, combined with varying complexity levels of the surface itself, a huge variety of coverage strategies can be defined, each with its own strengths and weaknesses in terms of total coverage, potential fiber defects, and structural properties of the overall resulting laminate. These results were published in CADA 2019 [63].
CHAPTER 3
AFP DEFECTS

This chapter discusses the various fiber defects that can occur during AFP manufacturing. It begins with an overview of the different expert perspectives that can be used when analyzing these defects known as viewpoint modeling. With this knowledge, several different aspects of the defects are cataloged, including methods for anticipation, measurement techniques, and the potential impact on the manufacturing process or the final manufactured laminate.

The clear definitions set forth in this chapter for each defect type become important in further chapters for ply analysis. A subset of these defects can be predicted and modeled through the interaction of the tool surface geometry and the fiber tows alone. The ability to model these defects enables an entire virtual layup to be built and analyzed before any manufacturing. The details of step optimization process are defined in Chapter 5.

3.1 VIEWPOINT MODELLING

To understand AFP defects, the source of the defect and how the part geometry influences the defect formation must be investigated. The current work begins with a thorough categorization of AFP defects to develop an understanding of the importance of defects from four different perspectives: the cause, anticipation, existence and significance. Each of these categories have a specific perspective of defining what is considered a defect. The cause category investigates the core cause or causes of a defect. The anticipation
category comes from the view of the process planner and investigates whether a defect can be expected with certain parameters in place. This category will show some possible parameter changes to avoid the defect. The existence category defines the defect from an inspection point of view and what the defect visually looks like. This category will indicate whether a defect is better suited for either a visual inspection or an automated or semi-automated inspection system. The significance category investigates the impact that a particular defect can have on a part if it occurs, either during manufacturing or during in-service performance. In addition, this section investigates what the defects can lead to if left unresolved.

3.2 DEFECT IDENTITY CARDS

The following provides a definition of 14 different defect types, along with a graphical representation, and discusses the relevance of the defect to the four points of views defined in section 3.1. Additionally, each card contains a CAD representation, and a picture of the defect occurring during the manufacturing process. These summaries are referred to as identity cards, as they contain the essence of their respective defects and can be easily referred to.

3.2.1 Gap/Overlap

![Figure 3.1 Gap/Overlap CAD Representation](image-url)
A gap occurs when two adjacent tows are not perfectly laid up adjacent to each other resulting in a gap between the tows. An overlap is when the two adjacent tows are overlapping onto each other. The most common cause of gaps and overlaps is steering during layup since, the tows in a course will not fit together perfectly, especially when adopting a parallel coverage strategy. However, gaps and overlaps can naturally occur outside of steering if laying up over a complex 3D tool surface.

Gaps and overlaps are well anticipated in areas of purposeful steering, or on doubly curved surfaces where adequate roller compaction is not guaranteed. From the geometry of these situations, the gaps and overlaps can be directly computed. The measurement of gaps and overlaps are generally easy to detect due to the build-up or lack of material along the course. As successive plies are laid up over overlaps, consistently at the same location at each layer, significant thickness buildup will be visible. A gap and/or overlap may become a site for failure initiation under loads. Gaps would create resin rich regions for crack growth while overlaps create undulation in the fiber that can lead to compressive failures. They may also become a site for wrinkling in the layers placed over them in the succeeding layer.

3.2.2 Pucker

![Figure 3.2 Pucker CAD Representation](image)
Puckers initiate at the inside radius of a steered tow, resulting in the tow lifting from the tool surface either partially or across the entire tow width forming an arch of excess material that is not adhered to the underlying substrate material. Puckered tows are caused by excess length of tow due to steering. This excess length of tow increases shear stress at the tow to substrate boundary overcoming the tack adhesion strength. If placement is over a compliant surface, with the force of the compaction roller, longer tows may be deposited that can form the pucker after the surface spring backs to its original shape.

Puckers can be prevented through appropriate towpath planning, since thickness buildup in concave shapes may cause shortening of the surface length, and the tow length fed out by the machine head may need to be shortened to compensate for the reduced length. Small puckers may be difficult to detect visually due to lack of contrast, so instead profilometry-based sensor detection system can be utilized to identify the puckered tow. Puckered tows are typically flattened by successive layers placed over them and by debulking. However, if the puckers are not properly compacted, it may result in a significant loss of strength.

3.2.3 Wrinkle

![Wrinkle CAD Representation](image)

Figure 3.3 Wrinkle CAD Representation

A wrinkle is typically indicated by a wavy pattern of puckering along the edge of a tow when it is steered through a non-geodesic path over a complex (potentially doubly...
curved) surface or following a steered path on a flat surface. These types of defects occur on the inner radius and remain out-out-plane after compaction and curing. Wrinkles are often caused by placing tows at small steering radii, which can lead to excessive differential length between the two edges of the projection of the tow on the part surface. The two edges of a tow delivered from the machine head are of equal length, hence part of the excessive differential length presents itself as puckers and/or wrinkles.

The steering radius definition and the complexity of the tool surface being laid up on are the main ways to anticipate a wrinkle. Tow path definition during design phase can have a strong influence on wrinkling behavior. Process parameters and tow material properties are also influential. Wrinkles can be detected either visually or using automated inspection systems but can be difficult to distinguish from puckers as the tow is overhanging along its orientation. Wrinkled tows covered by layers that are laid on top, force them to flatten during which in-plane fiber waviness or folded fibers may be caused. Additionally, wrinkles can cause gaps and folded tows which can result in a loss of strength.

3.2.4 Bridging

![Figure 3.4 Bridging CAD Representation](image)

A bridged tow does not fully adhere to the concave surface (female tool portion) or a re-entrant corner or ramp-up area over which the tows are being laid up on, leaving a gap
between the radius of the concave tool surface and the tow. The main causes of a bridged tow are too much tension on the tow, which will force the tow to lift, or insufficient tack adhesion to the surface being laid up on because the roller does not provide full contact with the substrate material.

The main ways to anticipate this defect are to ensure that the roller has the best contact coverage possible when going over a complex tool surfaces, especially concave portions. Overfeeding of the tow may eliminate bridging in re-entrant corners and ramps. Bridging is often readily identified visually and by automated inspection systems since the tow in question will be raised about the concave portion of the tool being laid up on. Successive passes of the roller to place additional layers with different orientations or de-bulking step with a vacuum may push the bridged tow to re-adhere to the substrate. However, the bridging could leave resin rich areas at best, or delamination at worst.

3.2.5 Boundary Coverage

![Figure 3.5 Boundary Coverage CAD Representation](image)

A boundary gap/overlap occurs when the material cannot perfectly meet up with the edge of a part when laying up at off-axis orientation such as ±45° in rectangular parts. Since the tows do not meet up perfectly with the edge, this will result in either an excess of material along that edge or a shortage between the tow-end and the boundary edge. This
can be at the boundary of any coverage zone, be it internal to the part inducing ply drop-offs, or at the external boundary.

This defect is a direct result of the chosen percentage of boundary gap and overlap defined during process planning and are additionally influence by the ply angle. These defects are clearly visible on the edges of any variable angle laminates and will be visible post-cure. A boundary gap and/or overlap can influence the shape of the part since the course will not line up with the desired geometry. If the edges are trimmed to ensure accuracy the part may be more likely to fail in the spots where the trimming occurred.

3.2.6 Angle Deviation

![Figure 3.6 Angle Deviation CAD Representation](image)

Angle Deviation is when the angle of the as-manufactured layup deviates from the as-designed one. Angle deviation can be caused by incorrect roller coverage or small radius steering as the tow may move after being steered. It also may result from necessary concessions made by the layup strategy in order to create coherent fiber paths.

The main way to anticipate angle deviation is through defining the steering radius for any required steering throughout the layup, since a smaller radius can cause angle deviation. Angle deviation is observed by visual inspection, but it requires further processing and comparison with the as-designed angles. Inspection systems alone cannot confirm the angle deviation without a benchmark for comparison. Angle deviation can
cause overlap on portions of the ply when a course will be laid up on top of the deviated tows. This can lead to an undesired shape in the laminate and can be a cause of failure due to resin rich areas on the counter side. This is a similar effect to overlap and gaps and can lead to delamination in the resin rich areas due to improper course coverage.

3.2.7 Fold

![Fold CAD Representation](image)

Figure 3.7 Fold CAD Representation

This defect occurs when the tow folds in the transverse direction onto itself, creating a gap in the surface coverage and doubling the tow thickness over the folded part. An extension (and probably the worst-case scenario) of the folding could be rolling (or completely twisting) of the tow to become “rope” like. Lack of or too much tension could increase the propensity of the tow to fold. Long unsupported/complex towpaths from the spools to the head can also result in folding. In a steered/curved towpath, the outer segment of the tow may fold towards the inner side after the compaction roller nip point due to tension on the outer edge of the tow and improper tack adhesion.

The quality of the slit-tape or tow will have a large influence on the folding defect, in addition to the machine’s type and calibration (health). Design has some influence if the towpath is steered. Process parameters (speed and temp) influence the tack adhesion. These defects can either be visually detected from variations in the courses surface, or via automated inspection systems. Twist are one of the more serious defect types for cured
laminates due to increased thickness right next to a reduced thickness region. Substantial influence on local fiber volume fraction variation, and creation of resin rich areas for failure initiation. These may also serve as sites for delamination initiation following the crack growth from the resin rich defect sites.

3.2.8 Twist

![Twist CAD Representation](image)

For this type of AFP defect, the tow is rolled axially 180° onto itself and then flattened by the compaction roller. Depending on the length over which the twisting occurs, the shape may be like a bowtie with bunching of the fibers and increased thickness at the center. For long twists, L>5t, the sides are simply folded. Twisted tow could be initiated by folding, in which the fold grows and completes a full turn rather than unfold (folded tow could be considered incomplete twist). Friction between guide holes, where material is fed from the material roll to the head, along a long/complex tow path and a tacky tow may cause twisting due to head rotation during bi-directional layups.

Twist may occur from the rotation of the machine head, the geometry of the part, or the tows not being properly fed into the machine. The geometry of the part contributes since a head rotation may be necessary on some portions of the part surface. Can be detected either visually or via automated inspection systems. Machine learning algorithms can be useful in classifying the defect as twist. Like folded tows, twisting roots causes a
portion of the part surface to not be covered with fiber, especially for long twists, and parts with increased thickness. A twist maybe more damaging than a fold, as structural load may cause scissoring deformation. Aside from being a source for cracking and delamination, severe deviation of the fiber paths within the tow from being straight will cause kinking failure of tows under compressive loads.

3.2.9 Wandering Tow

A wandering tow is when the portion of the tow between the roller and the cutter wanders from the original fiber path after being cut. Similar to “angle deviation”, wandering tows can be attributed to having an unsupported portion of the tow between the compaction roller and the tow cutter. Therefore, the angle deviation will only be of the dimension of this un-supported tow length.

The main approach to prevent a wandering tow would be to ensure that any steering has an appropriate radius or that the roller coverage is maximized to ensure proper adhesion. Wandering tows can be visually observed since they are typically located at the ends of a course. These defective tows can lead to a gap/overlap between tows which can result in a resin rich area and ultimately a higher chance of failure.
3.2.10 Loose Tow

A loose tow generally refers to a section of a tow (or tows) that the machine head attempts to place on a part without having complete and precise control over where it is placed, causing the tow to meander. A tow is completely loose when the length of a tow is shorter than the length between the cutters and the compaction roller. In this case, the tow is free to land on an arbitrary position. If at the end of a course the fiber path is still steered, the section of the tow before the compaction roller may not follow the defined steered path.

If the loose tow results in significant gap in the laminate, or a completely missing tow, then it can be detected visually or by automated vision systems. For steered tows, it will not be obvious if the tow is floating because of precision or because of course steering. If the loose tows are caused by steering, then their consequences have to be accounted for by using tools appropriate for it (if/when they exist) and may additionally cause unanticipated gap or overlap.

3.2.11 Missing Tow

This defect typically occurs when an entire tow does not correctly adhere and falls off the surface or is not successfully fed onto a surface from the spools. The resulting missing tow is very similar to a gap, and in fact can be considered as a gap with a size equal
to a tow width. Missing tows are caused by either discontinued material feeding into the machine head or layup of a tow with insufficient tack adhesion.

Figure 3.11 Missing Tow CAD Representation

Missing tows are not related to any designed features. Ensuring proper splices, and full material spools will eliminate accidental missing tow. On complex surfaces, providing enough compaction pressure, and ensuring sufficient material tack with proper temperature will preclude long bridged tows that may fall off the surface. The gaps created by missing tows are easy to detect either visually or through automated hardware. Like a gap, missing tows will cause local thickness variation, and potential resin rich pockets in the layup that can serve as a failure initiation point. This defect is a potential site for progressive delamination failure with the adjacent layers.

3.2.12 Splice

Figure 3.12 Splice CAD Representation

When two tows are joined by the material or slitting supplier end-to-end in a spool by overlapping 1 to 3 inches over each other and tacking them together. This results in a
portion of the spool that is thicker than the rest and is usually marked by white dashes for detection. Theoretically, carbon fibers can be drawn infinitely long. However, most AFP pre-impregnated tows are slit tape that are cut from a roll of finite length unidirectional tape. These slit tapes are spliced and spooled based on customer specifications.

Monitoring and keeping track of spool length for the splice locations with respect to the part size may eliminate the spliced tow from the part. Splices are difficult to detect visually if not marked. The thickness increase over the splice allows detection with a detection system. Thickness change over a small area may be insignificant for stiffness change. This site may become a location for failure initiation especially under compressive loads. Splices are possible sites for fiber kinking progression under compressive loads.

3.2.13 Position Error

![Position Error CAD Representation](image)

Figure 3.13 Position Error CAD Representation

A position error is when a tow is placed in a wrong location in reference to the end or beginning of a course. This results in a tow that is misaligned with the rest of the tows in the boundary. Main causes of this defect are either obstruction of the tow during feeding (such as building up of fuzz in one of the guide chutes of the machine head), or incorrect machine reference points with respect to the part for a particular course. Sometimes they are due to machine control issues and auto tuning requirements.
Position errors are arbitrary, and there is no way to anticipate them. However, ensuring that there is no material build up in the head of the machine that can cause resistance during layup and monitoring the accuracy of the layup simulation will reduce the possibility of an occurrence. These are similar to a tow gap near the part boundary, hence their influence compared to the regular defects are expected to be more pronounced due to edge-effect failures observed in multi-layered composites.

3.2.14 Foreign Object Detection

![Figure 3.14 FOD CAD Representation](image)

A foreign object debris (FOD) defect is when a small piece of composite material, either carbon fiber “fuzz-ball” or “resin ball or other debris from the production area fall onto the part during layup. This results in a small excess volume of material on the ply if laid up over. Monitoring the head of the machine and the production area for FOD and routine cleaning of surfaces are the appropriate ways to anticipate this defect. Large objects may be visually detected as it will be an irregular shape out of thickness along the same layer. A FOD defect in layup can cause the portion of the next ply above the defect to improperly adhere to the defect’s ply. This will lead to an undesired shape and strength of the part being made.
3.3 SUMMARY

This chapter has set forth a comprehensive list of AFP defects that occur during laminate manufacturing. These defects had several sources, including tool geometry, material and machine imperfections, and chance-based defects. Additionally, the detection techniques for each defect were provided as well as potential significance of the defect on the laminate. These results were published in SAMPE 2017 [64].
CHAPTER 4
PROCESS PLANNING FUNCTIONS

This chapter begins with a definition of the process planning functions that make up AFP process design and moves into the categorization and prioritization of these functions as defined by a process planning survey. These functions were developed to represent the individual steps taken in order to develop the NC code which can be run on a specific machine in order to create the independent part with the desired material system. As such, two major categorizations of these functions arose with respect to the specificity and the scope of the final design they have control over.

The primary functions are concerned with the geometry of the tool surface and can begin to make simple optimizations dependent on that geometry. Additionally, the material system’s stiffness and dimensions can affect these functions. The second category incorporates the machine’s capabilities into the desired path motions developed for the primary functions.

4.1 PROCESS PLANNING FUNCTIONS

The process planning functions presented in the following sections represent the basic steps taken by a process planner. These actions begin with an intended design and combine that the manufacturing resources and working material properties. The definitions which follow show how each of these steps transform the information and build up to the final product of efficient and reliable NC code.
4.1.1 Boundary Creation

![Boundary](image1.png)

Figure 4.1 Schematic of an example part boundary

The boundary (Figure 4.1) is the general border where the layup must end. It separates the furthest point the process planner wants the layup to be allowed to go from the point where the machine may be damaged by collision with obstacles on the mandrel such as holes, bumps, or vacuum bag openings.

4.1.2 Starting Point

![Starting Point](image2.png)

Figure 4.2 Schematic of an example starting point

The starting point (Figure 4.2) indicates from where the computational material coverage strategy will initiate. The starting point can change depending on the complexity of the mandrel, the complexity of the part’s geometry, and how much roller coverage there will be at a certain point. The starting point has an influence on the computation of the center path for the machine.
4.1.3 Tow Width Definition

The tow width definition (Figure 4.3) is the width of the tow that can be modified within the software to account for any error between the manufacturer’s tow width specification and the actual width of the tow. The error in the tow width is usually found by the process planner when they verify the dimensions of the tow and find a difference between the specified width and the actual.

![Figure 4.3 Schematic of an example tow width definition](image)

4.1.4 Layup Strategy

The layup strategy (Chapter 2) is the general strategy required for a specific part to be laid up on a given surface. These strategies will change based on both the part being laid up and the tool being laid up on.

4.1.5 Steering Constraints

![Figure 4.4 Schematic tow steering](image)

Steering constraints (and violations) are the restrictions a process planner will set on any steering necessary during the layup process. These constraints include the steering
angle and radius and will vary largely. They depend on the path algorithm chosen for the fabricated part, the curvature of the tool being laid up on, and the composite’s width and material properties [65], [66].

4.1.6 Interband Offset

An interband offset (Figure 4.5) is an offset that is placed in between courses during a layup. This offset will be used mainly to prevent any gaps or overlaps that may occur during layup, and especially while steering, but can also be used for any specific part geometry.

![Figure 4.5 Schematic of interband offset example.](image)

4.1.7 Stagger Shifts

A stagger shift (Figure 4.6) is when a process planner staggering two similarly oriented plies by shifting the top ply with respect to the bottom ply. A stagger shift is usually used when gaps or overlaps are present in a ply so that these defects do not propagate to a subsequent ply oriented in the same direction.

![Figure 4.6 Schematic of typical stagger shifts](image)
4.1.8 Boundary Coverage

Boundary coverage (Figure 4.7) is when the material cannot perfectly meet up with the edge of a part when laying up at angles that are not normal to the boundary, resulting in a gap or an overlap on that edge. The three common scenarios a process planner chooses from are a 100% gap-0% overlap, a 50% gap-50% overlap, or a 0% gap-100% overlap. This is especially important for internal boundaries as well (ply drops).

![Figure 4.7 Boundary coverage (0%, 50%, 100%)](image)

4.1.9 Dog Ear Addition

A dog ear (Figure 4.8) is additional material that is laid up at any corner of a part due to not being able to lay up perpendicular or parallel to that corner. Every machine has an absolute minimum tow length that it can lay up which causes dog ears to be present. The process planner will choose whether to implement these dog ears in the layup.

![Figure 4.8 Schematic dog ear additions](image)

4.1.10 Uni/Bi-Directional Layup

Uni-directional and bi-directional layups (Figure 4.9) are the difference between laying up a course in one or two directions. Different parts will benefit more from one or
the other depending on the part’s geometry and the off-part motion due to the complexity of the mandrel.

![Figure 4.9 Schematic of Uni/Bi-Directional layup](image)

4.1.11 Off-Part Motion

Off-part motion (Figure 4.10) is the amount of movement the machine must make between laying up courses while off the machine. The most efficient off-part motion will vary from machine to machine and from part to part.

![Figure 4.10 Schematic of example off-Part motion](image)

4.1.12 Feed Rates

The feed rates are the layup, add, and cut zone speeds for tow placement while laying up a part. These speeds determine how quickly or slowly the machine will layup and at what rate the machine will start layup and cut material during the layup process. In this stage of process planning the optimal feed rates will be found based on the selected layup strategy.

4.1.13 Axes Weights

The axes weights (Figure 4.11) are how the different machine axes are weighted at any point throughout a layup. Assigning a higher weight to an axis indicates that it will
generate more of the machine motion during travel. In weighing the axes differently throughout the layup, a process planner can create a more efficient layup depending on the necessary layup strategy and the complexity of the tool. Properly weighing the machine axes is important in the post processing stage, as some axes will have different maximum velocities and accelerations depending on the machine kinematics.

![Figure 4.11 Image of the AFP machine indicating axes weight directions](image)

4.1.14 Angles of Tilt

The angle of tilt for the machine (Figure 4.12) is what defines the tilt of the head of the machine during layup. The tilt of the machine’s head will vary depending on the geometry of the part and the complexity of the mandrel being laid up on in order to maximize roller coverage. This function is based on machine configuration and investigates extreme opposed tilts.

![Figure 4.12 Image of McNair AFP head showing typical angles of tilt](image)
4.1.15 Course Efficiency

The course efficiency (Figure 4.13) of a part is how efficiently the courses are laid up due to their dimensions, which is usually reviewed before or during simulation. Course efficiency investigates where partially empty courses can be eliminated by merging with other partially empty courses. However, merging courses must not interfere with the imposed course stagger which intends to minimize coincident course edges through the laminate.

![Schematic of course efficiency examples](image)

Figure 4.13 Schematic of course efficiency examples

4.2 PROCESS PLANNING SURVEY

The Computer Aided Process Planning (CAPP) survey was developed and distributed to receive feedback on the principal process planning functions from the ACC CRT industry partners with AFP process planning experience. The functions on the survey were rated for their relevance and importance, expectations for automation, and time consumption during the process planning stages. Additionally, an open-ended question allowed the CRT members to define the expected output of the function. The final goal of the survey was to help emphasize and prioritize the process planning functions to be investigated in depth and apply useful levels of automation.
Table 4.1 CRT entity survey participation

<table>
<thead>
<tr>
<th>CRT Entity</th>
<th>Total Surveys Returned</th>
<th>Total Contributors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collier</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Spirit</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Aurora</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Boeing</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 4.14 Snapshots of the survey information page and sample function

The survey was distributed to the ACC CRT industry partners on November 2, 2017 and collected throughout the month of December 2017. Surveys were returned from Aurora, Boeing, Collier and Spirit. A total of five surveys were returned from a total of nine contributing experienced aerospace industry AFP engineers (Table 4.1).
4.3 CAPP FUNCTION SURVEY ANALYSIS

The survey analysis identifies the key points that were presented by each survey and summarizes the voting results for each question. Each of these comments helps to clearly identify the inputs and outputs expected from each function. The results of the survey are presented through the tables included in Section 4.3.

4.3.1 Quantitative Assessment

A quantitative summary of the survey is presented in Figure A. through Figure A.4. Figure A. assesses if the respondent believes that the function is important to the process planning workflow and Figure A.2 if automation is desired for the said function. In Figure A.3, the importance of the function is assessed and in Figure A.4 the estimated amount of time the function currently consumes in the process planning work-flow is shown.

Table 4.2 Prioritizing functions

<table>
<thead>
<tr>
<th>Functions (voted importance)*</th>
<th>% of Process Planning Agreeance (votes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layup Strategy (5 Y – 0 N)</td>
<td>80 % (5)</td>
</tr>
<tr>
<td>Dog Ear Addition (5 Y – 0 N)</td>
<td>80 % (5)</td>
</tr>
<tr>
<td>Stagger Shifts (4 Y – 0 N)</td>
<td>80 % (5)</td>
</tr>
<tr>
<td>Steering Constraints (4 Y – 0 N)</td>
<td>80 % (5)</td>
</tr>
<tr>
<td>Uni/Bi-Directional Layup (4 Y – 0 N)</td>
<td>75 % (4)</td>
</tr>
<tr>
<td>Off-Part Motion (4 Y – 0 N)</td>
<td>75 % (4)</td>
</tr>
<tr>
<td>Feed Rates (4 Y – 0 N)</td>
<td>75 % (4)</td>
</tr>
<tr>
<td>Axes Weights (4 Y – 0 N)</td>
<td>75 % (4)</td>
</tr>
<tr>
<td>Angles of Tilt (4 Y – 0 N)</td>
<td>75 % (4)</td>
</tr>
</tbody>
</table>

4.3.2 Prioritization of Process Planning Functions and Grouping

By comparing the voting results from the survey, a list of functions ranked by their importance was generated (Figure A.). Only functions that were deemed important by each of the surveys were included in the selection, presented below in Table 4.2 which only
includes functions with complete agreeance from Figure A.. Some participants abstained from answering on some questions, therefore the number of surveys doesn’t necessarily reflect on the number of total votes.

Based on the results from Table 4.2 and with regards to the additional remarks included with the survey, an informal grouping of the described process planning functions into three groups was created. Group 1 contains the process optimization functions list in Table 4.3. Group 2 is oriented towards the toolpath optimization functions listed below in Table 4.4. The miscellaneous functions were added to Group 3 in Table 4.5.

4.4 PROCESS OPTIMIZATION FUNCTIONS

The group of functions that ranked the highest in terms of priority for automation are shown in Table 4.3. The table described the function number, the function title, the expected output, as well as the additional received remarks. The functions of this group can be accurately modeled strictly with material and tool surface dimensions. Therefore, they are the primary candidates to work towards automating.

4.5 TOOLPATH OPTIMIZATION FUNCTIONS

The group of functions that ranked second in terms of priority for automation are shown Table 4.4. These functions combine the courses paths developed from the algorithms presented in Chapter 2 with machine specific information in order to create the final NC code. Therefore, intimate knowledge of the AFP platform is necessary to implement these functions.
Table 4.3 Group 1: Process Optimization Functions

<table>
<thead>
<tr>
<th>#</th>
<th>Function Title</th>
<th>Expected Output</th>
<th>Additional Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Layup Strategies</td>
<td>▪ Provide a set of metrics for each layup strategy relevant to defect likelihood</td>
<td>▪ Determined by engineering with some input from numerical control programming</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ Optimize based on user priorities such as angle deviation, steering, gaps/laps, etc.</td>
<td>▪ Choose the strategy that minimizes buildup of defects through the laminate’s thickness</td>
</tr>
<tr>
<td>9</td>
<td>Dog Ears</td>
<td>▪ Modify ply boundaries to account for additional material placement</td>
<td>▪ Unless specifically defined by engineering, accept default dog ear method applied by software package</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ Determine optimal dog ear strategy by structural analysis</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Stagger Shift</td>
<td>▪ Reduce coincident laps/gaps through laminate thickness through modification of the starting point</td>
<td>▪ Consider the importance of reducing the feature that stagger shift is attempting to minimize</td>
</tr>
<tr>
<td>5</td>
<td>Steering Constraints</td>
<td>▪ Dynamically vary the acceptable steering radius over the surface depending on local curvature</td>
<td>▪ Only suggest minimum steering radius as guideline, since the surface curvature will alter the effects of in-plane curvature</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ Recommend minimum steering radius based on geometry and layup orientation</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Starting Point</td>
<td>▪ Minimize steering error, gaps, overlaps, and angle deviation, in addition to meeting course stagger requirements by placement of the starting point</td>
<td>▪ Finding proper placement varies by path generation algorithm, and can be a tedious, but critical action</td>
</tr>
</tbody>
</table>
Table 4.4 Group 2: Toolpath Optimization Functions

<table>
<thead>
<tr>
<th>#</th>
<th>Function Title</th>
<th>Expected Output</th>
<th>Additional Remarks</th>
</tr>
</thead>
</table>
| 10 | Uni/Bi-Directional Layup       | ▪ Select the fastest method by default, but retain the user’s ability to force a specific method  
▪ Account for the speed of specific machine axes required during method selection | ▪ Account for tool access, potential collisions, and current machine status during method selection            |
| 11 | Off-Part Motion                | ▪ Select route which connects courses to produce fastest possible time  
▪ Selection of routing should account for the status and potential tooling collisions | ▪ Depends on the Uni/Bi-directional setting chosen  
▪ Affects part quality at the start and end of courses, and determines the approach and exit settings from each course |
| 12 | Feed Rates                     | ▪ Generated as a function of the part geometry, material properties, and machine capability  
▪ Optimized down to the course level                                                                                   | ▪ Affects process reliability and sensitivity to working conditions                                           |
| 13 | Axes Weights                   | ▪ Find weights which result in fastest times, and identify the limiting axes for specific part geometries  
▪ Identify which weights result in the best layup accuracy                                                              | ▪ Necessary to avoid axis limits and singularities during layup  
▪ Selection of weights are more of a numerical control programming responsibility                                           |
| 14 | Angle of Tilt                  | ▪ Recommend machine tilt in areas where machine-tool collisions are present  
▪ Adjust machine lead and lag to optimize compaction for surface contours and to reduce material bridging | ▪ Improve laminate quality through angle of tilt                                                                |
### 4.6 MISCELLANEOUS FUNCTIONS

The group of functions that had lower automation priority for the process planner are shown in Table 4.5. These functions can be grouped into the previous two categories for geometry or machine concepts. However, due to their low automation interest, they have been grouped here.

**Table 4.5 Group 3: Miscellaneous Functions**

<table>
<thead>
<tr>
<th>#</th>
<th>Function Title</th>
<th>Expected Output</th>
<th>Additional Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Boundary Creation</td>
<td>▪ Optimized ply boundaries for boundary coverage and dog ear generation</td>
<td>▪ Size boundaries for laminate specifications to account for ramping to subsequent plies</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ Account for user input for the generation of machine boundaries</td>
<td>▪ Enforce engineering rules regarding overstuffing, but are limited to specific applications</td>
</tr>
<tr>
<td>3</td>
<td>Tow Width Definition</td>
<td>▪ Define tow width with respect to machine abilities</td>
<td>▪ No automated tools exist to determine optimal tow width for a given geometry and path generation algorithm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ Account for steering and contour when deciding tow width</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Interband Offset</td>
<td>▪ Account for course width deviation from nominal values that result from machine effects</td>
<td>▪ Most relevant to areas of course convergence, and the allowed offset must follow engineering requirements</td>
</tr>
<tr>
<td>8</td>
<td>Boundary Coverage</td>
<td>▪ Monitor over/under-fill created by boundary coverage strategies</td>
<td>▪ Effects proportional to width of tows/tapes, more relevant when material width exceeds 3.81 cm (1.5 in)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ Consider primarily around interior boundaries, and predict its effects on ramping for subsequent plies</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Course Efficiency</td>
<td>▪ Driven by starting point and stagger shifts, so updates to those parameters are necessary to modify course efficiency</td>
<td>▪ Diminishing impact as ply size increases relative to the chosen course width</td>
</tr>
</tbody>
</table>
4.7 CONCLUSION

This chapter has defined the process planning functions and explained what types of information they require, and what results and impact they may have on the manufacturing and structural properties of the laminate part. Additionally, the processing planning survey and its results were presented. The survey performed by skilled process planners allowed for prioritization and refinement of the scope of each process planning function. From these results, a natural grouping of the functions into different phases was developed. Finally, a set of functions were identified for implementation in an automated fashion.

The results of this chapter have previously been published in SAMPE 2019 [67].
CHAPTER 5
PLY LEVEL OPTIMIZATION

The creation of the best layups can be approached as an optimization problem. In order to perform this optimization, it is necessary to quantify and score the layups generated with the strategies defined in Chapter 2. For this approach, a ply level optimization is performed, where each ply is individually tailored in order to minimize its objective function. The objective function allows us to quantify the resulting plies according to the following sets of inputs and outputs.

The inputs will be two of the functions defined in Chapter 4, the starting point (section 4.1.2) and the chosen layup strategy (section 4.1.4). These are two of the functions that were identified from the process planning survey as benefiting from some automation, additionally these have a very direct effect on the resulting ply. The outputs are the defects directly resulting from the geometrical relationship between the tool surface and the created plies. The defects chosen here were gaps and overlaps (section 3.2.1), angle deviation (section 3.2.6), and fiber steering. Fiber steering can be directly measured from the geometry of the created fiber paths and can lead to several other defects: puckers (section 3.2.2), wrinkles (3.2.3), and folds (3.2.7).

This chapter will define the techniques used for measuring the fiber defects and how they are used to create the objective function. Following this, the iterative method used to approach an optimized ply using the objective function is described.
5.1 MEASURING FIBER DEFECTS

5.1.1 Measuring Gaps and Overlaps Occurrences

Fiber gaps and overlaps are coupled defects that occur when adjacent tows are not perfectly parallel. The deviation of alignment results in a fiber path that will drift towards or away from its neighbors. These features are coupled since deviation resulting in an overlap with one neighbor will often result in a gap forming with the other adjacent neighbor.

![Overlap and Gap](image)

Figure 5.1 Example of the coupling of Gaps and Overlaps in a laminate

The most common cause of gaps and overlaps during the process planning and simulation phase is the use of excessive steering for curved paths, and surfaces with high levels of double curvature, those which are non-developable. Often for these scenarios, it is impossible to completely remove the presence of gaps and overlaps. Gaps and overlaps may be a site for failure initiation under loads, where gaps create resin rich regions for crack growth, while overlaps create undulation in the fiber that can lead to compressive failures. For these reasons it is important to reduce the presence of gaps and overlaps to improve the final properties of the laminate.

The measurement of gaps and overlaps requires the parametric tool surface and the generated layup paths to be investigated. The process initially relies on the translation of
the paths on the Cartesian tool surface, to the parametric space that represents the tool surface.

Figure 5.2 (a) Cartesian representation of the tool surface and ply paths; (b) Parametric representation of the ply

With the 2D representation of the ply, gaps and overlaps are detected through basic polygon boolean operations. Overlaps are found as the intersection of any combinations of courses, where gaps are developed from the total tool surface area minus the union of the courses.

Figure 5.3 Ply courses (yellow), areas of overlap (red), areas of gaps (blue)
\[ \text{Area}_{\text{overlaps}} = \sum \cap_{\text{paths}} \] (5.1)

\[ \text{Area}_{\text{Gap}} = \text{Area}_{\text{Surface}} - \cup_{\text{paths}} \] (5.2)

The area of overlaps and gaps are returned as sets of individual polygons, representing each instance of these defects as they occur for the given ply. It is possible to then visualize these regions as they occur within the ply to determine occurrences and density of defects.

5.1.2 Measuring Fiber Angle Deviation Occurrences

For rosette angles to be applicable to non-planar surfaces, it is necessary to describe referential coordinate system over the domain of our surface to serve as the basis for the angle deviation measurements. In this context, the referential coordinate system of each quad was used to generate the base vector.

![Figure 5.4 Unit normal vectors at the center of each quad mesh element](image-url)
5.1.2.i  **Mapping Path to Mesh Elements**

The current method generates an angle deviation value for each relevant mesh element. A mesh element is relevant when it contains a portion of the course and can thus generate an angle deviation value. The mapping method relies on the $uv$ mapping of the surface, which is generated as a simple grid. The grid structure conveniently allows for binning, Figure 5.6, of the $uv$ values of each course in order to find the containing mesh elements as depicted in Figure 5.7.

5.1.2.ii  **Calculating Angle Deviation Instances**

The directions of the courses are developed from their normalized tangential vectors along the path as in Figure 5.8.
The manufacturing angle along each path can be found relative to the relevant referential coordinate systems that were previously mapped. The vector dot product relation (5.3) allows for the calculation of the angles.

\[ \cos \theta = \frac{\vec{u} \cdot \vec{v}}{||\vec{u}|| \cdot ||\vec{v}||} \] (5.3)

The angle deviation was computed by comparing the measured manufacturing angle to the design angle as defined by equation 5.4.

\[ \text{Angle Deviation} = \text{Design Angle} - \text{Manufacturing Angle} \] (5.4)

### 5.1.3 Measuring Fiber Steering Occurrences

The use of fiber steering (Figure 5.9) allows for optimization of laminate loading properties in addition to altering laminates to avoid defects due to the presence of certain tool geometries. Fiber steering achieves these effects by changing the in-plane curvature of the fiber path from the classic linear orthogonal laminates.
However, due to the high modulus of elasticity of carbon fiber, the curvature from fiber steering results in tensioning of the outer edge of the fiber tow and compression of the inner portion of the fiber tow. These conditions may result in several defects such as gaps and overlaps, puckers, wrinkles, and etc. Therefore, steering constraints are necessary during the process planning stage to limit the magnitude of fiber steering and thus reduce the occurrence of defects generated by steering of the tows. A process planner will choose the limit based on his knowledge of the machine’s steering abilities and the steering characteristics of the particular fiber-matrix combination to be used.

5.1.3.i Measuring fiber steering

Fiber steering is defined as the difference between the curvature of a fiber path and the geodesic curvature of the tool surface. The closed form of curvature for spline curves presented by 5.5.

\[
k_g = \left[\left(u'_c + \Gamma_{11} u'_c^2 + 2 \Gamma_{12} u'_c v'_c + \Gamma_{22} v'_c^2\right)v'_c - \left(v'_c + \Gamma_{11} v'_c^2 + 2 \Gamma_{12} u'_c v'_c + \Gamma_{22} v'_c^2\right)u'_c\right] \times \frac{\sqrt{E G - F^2}}{\left(E u'_c^2 + 2 F u'_c v'_c + G v'_c^2\right)^{3/2}} \quad (5.5)
\]

5.2 DEFECT INSTANCES AND SEVERITY

Process planning works to minimize defects and unwanted features that will develop based on the chosen process planning parameters. Currently, there are techniques in place that are able to measure these defects in a case by case basis but lack the ability to summarize the defects on a ply-wide scale. Additionally, there is no system to compare the presence of defects on a common scale where they may be used to generate a logical, overall ranking for a generated scenario depending on the requirements set forth by the process planner.
To summarize these features, two aspects of their presence must be considered. The majority of manufacturing and design processes set a maximum instance threshold for each feature. An instance threshold measures total amount of defects above a certain threshold. These limitations are imposed to reduce the propagation of more defects and to improve the manufacturability of the laminate.

The other measurement used by process planners is severity. The severity threshold of the defect finds the amount that the instances above the threshold value affect the total amount of defects. This measures how significantly certain defects will affect the overall laminate and will demonstrate if there are many small defects or several large defects.

The Instance functions as an indicator of commonality of the features for the given ply. The Severity of the feature uses the threshold to find the sum of the instances as they occur in the ply.
To help better explain Instance and Severity Values it is helpful to go over Figure 5.10. These graphs represent hypothetical defect graphs that are implemented into the CAPP module. The x-axis is the size of the defect and the y-axis is the number of times a defect at that size occurs. The red vertical line represents a threshold value. Graph 1 and 2 would have the same number of instances above the threshold but the severity would be more dramatic in graph 2 since there are more defects that are larger. Graph 3 would have both a high instances and high severity while Graph 4 would have instances at around 50% but severity would be closer to 75%.

The Instance and Severity measurements function together to provide a common scale to measure instances that occur beyond a set threshold value. The following paragraphs will detail the 4 selected features (Gap, Overlap, Angle Deviation and Steering). For each, a clear definition is presented with respect to the instances and severity.

5.2.1 Summarizing Gap and Overlap Occurrences

5.2.1.i Gap and Overlap Instances
The gap and overlap instances measures the percentage of occurrences of “unacceptable” gap and overlap regions that occur within the ply. The overlap instances is defined by 5.6 and gap instances by 5.7.

\[
O_L = \# \left( \text{Area}_{\text{Laps}} > O^T_L \right) \tag{5.6}
\]

\[
G_L = \# \left( \text{Area}_{\text{Gaps}} > G^T_L \right) \tag{5.7}
\]

5.2.1.ii Gap and Overlap Severity
The gap and overlap severity measure the percent coverage of the layup that results from gaps or overlaps. The gap and overlap severity are defined by 5.8 and 5.9.
\[ O_v = \sum (Area_{Laps} > O_L^T) \]  \hspace{1cm} (5.8)

\[ G_v = \sum (Area_{Gaps} > G_L^T) \]  \hspace{1cm} (5.9)

5.2.2 Summarizing Angle Deviation Occurrences

5.2.2.i Angle Deviation Instances

The angle deviation instances measure what percent of each course exceeds the designer set maximum allowable angle deviation value. The process planner inputs this maximum value as a measurement in degrees. With this knowledge, the severity of the angle deviations can be determined as they occur in each course.

5.2.2.ii Angle Deviation Severity

It is important to find the angle deviations above a certain threshold that exceed a certain tolerance. The angle deviation tolerance is a subjective value to be determined within the engine itself. For example, if 5 degrees was chosen, this would identify that any angle deviation of 5 degrees or less is deemed “acceptable”. This allow the engine to distinguish between minute imperfections and legitimate angle deviation conflicts.

The Severity would represent a total angle deviation value for an entire course. It represents a type of angle deviation area for each course, where acceptable paths would receive a value of zero, and courses of higher angle deviation would tend to a Severity of 100%. The Severity would be computed by integrating the entire angle deviation curve to serve as the divisor, and the sum of the integrals above the maximum angle devotion level would represent the operand.

5.2.3 Summarizing Fiber Steering Occurrences

5.2.3.i Fiber Steering Instances

The steering level measures the percentage of occurrences of “unacceptable” steering violations that occur within the ply. The overlap instances are defined by 5.10.
\[ S_u = \# (\text{Curvature}_s > S_u^T) \] (5.10)

5.2.3.ii Fiber Steering Severity
The steering severity would represent a total steering summary for an entire course. It represents a type of steering violation area for each course, where acceptable paths would receive a value of zero, and courses of steering would tend to a severity of 100%. The severity would be computed by summing the entire steering measurement along the curve to serve as the divisor, and the sum of the steering above the maximum steering threshold would represent the operand (Figure 5.11).

![Figure 5.11 Computing value from steering values along paths](image)

5.2.4 Instance and Severity example
Here is a basic example of how the instance and severity values were computed from the defect threshold. Below is a chart and image depicting the “Feature Threshold Values” for a hypothetical layup. The defect investigated will be gaps.

![Figure 5.12 Gap and Overlap Example](image)
Table 5.1 Instance and Severity measurements resulting from given threshold

<table>
<thead>
<tr>
<th>Defect Instances</th>
<th>Threshold</th>
<th>Instances</th>
<th>Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td></td>
<td>.2</td>
<td>.5</td>
</tr>
</tbody>
</table>

The space between the tows represents the gaps and the numbers above show the gap size. For this example, since our threshold is 1.1, only defects with an area larger than the threshold value of 1.1 are selected.

There is one instance of a defect larger than this out of a total of five defects:

\[ G_{\text{Instances}} = \frac{1 \text{ instance of a defect larger than 1.1}}{5 \text{ total instances of gaps}} = \frac{1}{5} = .2 \]

Therefore our “feature measurement” value for gap instances would be .2. The gap severity measures the percent coverage of the layup that results from gaps above the threshold. For our example there is a total area of 4mm for gaps that are larger than 1.1mm out of a total area of 8mm.

\[ G_{\text{Severity}} = \frac{\text{Total gap area resulting from instances of defects greater than 1.1 mm}}{\text{Total area resulting from all defects}} = \frac{4}{8} = .5 \]

Therefore, our “feature measurement” value for gap severity would be .5 for a threshold of 1.1. Instances capture the number of defects while Severity monitors the impact of the defects. The next section will discuss how the process planner can assign a relative importance to each defect.

### 5.3 COMPARISON AND RANKING

The Analytical Hierarchy Process (AHP) provides a method for creating an overall ranking of many features through a series of pair-wise comparisons. These comparisons are then used to develop a relative weight for each of the fiber defect variations.
Figure 5.13 (a) AHP Matrix filled with input from Process Planner; (b) AHP Matrix processed to retrieve final rankings

The value of relative importance between each pair of defects were entered into the upper half of the matrix and signifies how much the column is preferred over the row criteria. By doing this, the bottom half of the matrix is automatically computed as the inverse values of the upper half as seen in Figure 5.13a. From there, the sum of each column is computed and divides the value in each column to achieve Figure 5.13b. The final weights of Figure 5.14 are achieve by average the values of each column in Figure 5.13b. These final weights represent the relative importance of each type of defect and are utilized in the objective function.

<table>
<thead>
<tr>
<th>Weights</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gap Instances</strong></td>
<td>22.3%</td>
</tr>
<tr>
<td><strong>Overlap Instances</strong></td>
<td>19.3%</td>
</tr>
<tr>
<td><strong>Angle Dev. Instances</strong></td>
<td>18.0%</td>
</tr>
<tr>
<td><strong>Steering Instances</strong></td>
<td>12.9%</td>
</tr>
<tr>
<td><strong>Gap Severity</strong></td>
<td>9.5%</td>
</tr>
<tr>
<td><strong>Overlap Severity</strong></td>
<td>5.5%</td>
</tr>
<tr>
<td><strong>Angle Dev. Severity</strong></td>
<td>6.2%</td>
</tr>
<tr>
<td><strong>Steering Severity</strong></td>
<td>6.3%</td>
</tr>
</tbody>
</table>

Figure 5.14 Resulting defect weights
5.4 ITERATIVE OPTIMIZATION APPROACH

Due to the time required to compute the ply from the specified inputs, it is not currently feasible to test every possible pair of inputs, so instead an iterative approach is used. Each ply is initially defined by a ply boundary and ply angle. These provide the basis for the defined plies of the laminate; therefore, the ply boundary and ply angle can be used to create several variations of each ply. These variations of inputs for each ply create what is known here as ply scenarios and serve as the inputs to our objective function.

The objective function uses the data that is defined in sections 5.2 and 5.3. The summary of the ply’s defects and the selection of the defects to prioritize are combined to create a normalized value quantifying each ply. The chosen rankings apply weights to our defects, such that the most highly ranked defects impart the most to the overall value. Therefore, it is necessary to minimize our objective function in order to produce the ply with the lowest amount of the prioritized defects.

The first step in the optimization begins by creating a localized grid of points at the HKS center of the geometry as in Figure 5.15a. The grid points are oriented with the specified ply angle and are initially spaced by half a tow width. Each grid point represents a starting point for a different ply scenario, and each point may utilize several different layup strategies. Each of these ply scenarios are processed and scored using the defined objective function.
Following iterations, ply scenarios, as in Figure 5.15b, are generated using the starting point and layup strategy with the lowest score. Iteration to the optimal ply solution can be stopped after reaching an acceptable number of defects, or when a certain amount of time has elapsed in computing each round of ply scenarios.

5.5 CONCLUSION

The methods set forth in this chapter enable the quantification and optimization of ply scenarios. This quantification was a function of both the resultant geometrical defects from the layup process and the rankings set by the process planner. The geometrical defects were measured as functions of their instances and severity, where the combinations of both these measures were meant to summarize the extent of the defects. These measurements were combined with the one-to-one ranking process enabled by the AHP and resulted in single normalized scores for each ply scenario. The starting point optimization was performed by considering the distribution scores from the previous iteration. New grids of starting points were generated around the previous best score, and as many iterations as required could be performed.
CHAPTER 6
COMPUTER AIDED PROCESS PLANNING

The goal of the Computer Aided Processes Planning (CAPP) software is to implement and appropriately automate the process planning functions identified in the down selection process of Chapter 4 and further expanded upon in Chapter 5. The following chapter discusses the creation of the CAPP software and how it aids in the rapid prototyping design phase of composite laminates along with the ply level optimization to reduce geometry related fiber defects. The methods laid out will ultimately help find the ideal starting points and layup strategies to reduce the fiber defects.

The CAPP software is broken down into three major functions. First, the software helps to create several ply scenarios by locating starting points with potential layup strategies and presents the resulting geometrical fiber defect instance and severity measurements. The second portion allows the process planner to define the relative importance of defect types in order to create an overall ranking of the defect set that is used for the ply level optimization. The final function presents final scores for each ply scenario and organizes them by starting point and the chosen layup strategy. These scores can be used to decide if a satisfactory solution has been reached or if additional iterations should be performed. Minimizing the ply’s overall score, or objective function, indicates that a solution has been reached which adequately minimizes the prioritized defect types. These
functionalities are defined as the three “Majors” of the software and are described in sections 6.5, 6.6, and 6.7.

Before continuing into the description of the CAPP itself, it is important to discuss how the CAPP module has been integrated into a higher-level workflow for the reduction of fiber defects and their impact on a laminate’s structural properties. The following section describes the inter-software communication that occurs to achieve this overall laminate optimization of which the CAPP is a part of.

### 6.1 INTER-SOFTWARE COMMUNICATION

The purpose of inter-software communication is to leverage well developed functionality that is contained within pre-existing tools. Utilizing these other tools enables abstraction and new functionality of their methods. The CAPP software takes a similar approach, utilizing several other software solutions, namely Collier Research’s Central Optimizer (CO) and CGTech’s Vericut Composite Programming (VCP). The flow of communication is presented in Figure 6.1.

![Figure 6.1 Software flow diagram](image-url)
The flow diagram presents the CAPP’s relationship with the other software and which types of data are shared during each step to achieve the laminate optimization. The process begins with the CO, which passes the basic laminate definitions to the CAPP. These laminate definitions contain the tool surface on which the laminate will be constructed as well as the ply boundary and ply angles that define each individual ply in that laminate. The CAPP takes this laminate definition and constructs and enters the ply level optimization loop with VCP. Here, different laminates are iterated upon to minimize the prioritized defects. VCP enables this iteration by building the geometry of the ply scenarios supplied by the CAPP and identifying the resulting geometric defects. After a sufficiently optimized laminate has been generated, the process planning results can be used to continue the laminate design phase.

The remaining sections of Chapter 6 present the software interface and explain the CAPP’s own software workflow. The goal is to gain a better understanding of the CAPP module, and how it is capable of incorporating the optimization scheme defined in Chapter 5 in order to benefit the laminate design process.

6.2 SOFTWARE INTERFACE OVERVIEW

The CAPP software is a standalone package that can opened to the following interface presented in Figure 6.2. The individual portions of the software are presented and described in the following sections in the order that typical user would interact with them.

6.2.1 Laminate Tree

As stated previously, the CAPP module begins by opening a laminate definition and a surface path that have been defined by the CO. The interface looks like the one
presented in Figure 6.3a. The structure of the laminate can be observed in Figure 6.3b, where each ply, its ply angle, boundary name, and its various ply scenarios are organized.

Figure 6.2 CAPP Opening Screen Snapshot

Figure 6.3 CAPP laminate tree

6.2.2 Viewer Options

Once the analysis is complete and the VCP results are reimported into the CAPP module then many of the viewer options can be used. These options help visualize the tool and the defects giving the process planner a better understanding of the manufacturability
of the part. The viewer options are shown in Figure 6.4a-b along with the tooltip of their functionality.

The viewing options, especially the defect toolbar, work in close tandem with options in Major 1, and can only be used when the specific types of data have been analyzed and imported to the CAPP software.

![Viewer Options](image)

(a) Visibility Viewer Options; (b) Defect viewer options

6.2.3 Operations and Batch Analysis Interfaces

The initial state for optimization is created through the interface featured in Figure 6.5. This set of functionality performs the surface splitting, HKS computation, and surface center point discovery for each ply contained in the laminate. In the same toolbar, there is also the option to create the next iteration and refresh the viewer. This process can also be done individually by right-clicking any of the plies.
These buttons create the data necessary for the generation of the initial VCP batch file for layup simulation and defect identification. The tool bar in Figure 6.6 contains the functionality for generation of the VCP file creation and allows the use of batch templates. This also features the button for importing the output of the VCP analysis.

6.3 CREATION OF PLY SCENARIOS

The CAPP’s initial function is to find the starting points for different tools and boundaries and then export these to the Vericut Composites Program (VCP) software. As
regularly stated in section 4.1.2, finding the correct starting point is a critical function of process planning. Finding the correct starting point can be a tedious and difficult task that benefits greatly from automation. To help reduce the time for this task the CAPP module finds an array of starting points for each ply.

The following section discusses how the starting points are located. The CAPP module takes in a Catia Laminate consisting of a laminate definition and surface path. This sets up the ply boundaries and tool surface as seen below in Figure 6.7.

The starting points can now be identified for all the plies that create the laminate. The CAPP module performs the following three steps in order to identify the starting points: Splits the surface at the ply boundary so only the area inside the surface is worked on; finds the Heat Kernel Signature (HKS) on the area inside the ply boundary; create an array of starting points where the HKS is the “hottest”. The process is relatively simple but greatly reduces the time it takes for process planners to find starting points. With three
clicks, the starting points for all the plies can be generated. The following contains a detailed explanation of each of these steps.

In step 1, the software locates the ply boundary and isolates the surface inside as in Figure 6.8a. This is important so that HKS calculations occur in the correct area and the starting points for the specific ply being worked on are found.

In step 2, the software performs an HKS calculation on the part. This essentially heats up the part and sees where the heat is last to dissipate from. The results of an HKS calculation can be seen in Figure 6.8b.

The final step creates an array of starting points at the “hottest” part of the tool as indicated by the HKS results. An array of 9 potential starting points is placed on the part. Having an array of starting points will help create iterations later to find the best possible starting point.

Each starting point will have a specific layup strategy associated with it. These layup strategies are created in VCP and use the principles set out in Chapter 2. The process planner will have the option of choosing which layup strategy they want each time they create a starting point array.
Once these ply scenarios have been generated through this portion of the interface, the functions from section 6.2.3 can be used to create the files necessary for the batch processing functionality of VCP.

**6.4 BATCH PROCESSING OF PLY SCENARIOS**

Once the ply scenarios have been initialized, the CAPP module can create a VCP batch file which contains their ply definitions. This batch file is imported into VCP where the specified starting points are investigated with their associated layup strategies. VCP generates the plies from these ply scenario definitions and finds the defects present. The gaps, overlaps, angle deviation, and steering angle defect results are included in a report that is imported back into the CAPP module. These results are utilized by the workflow in Major 1, 2, and 3.
Figure 6.10 VCP Defect Analysis

Figure 6.11 VCP Batch Functionality Manager
6.5 MAJOR 1: EXTRACTION OF TOOLPATH INFORMATION

Major 1 is the first area where the process planner’s preferences come into play. Here a unique analysis of each layup strategy can be created depending on the operator’s preference. Major 1 develops a set of instances and severity measurements for each feature of interest. The operator will set the maximum threshold values for the gap, overlap, angle deviation, and curvature steering defects as presented in Figure 6.12.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Threshold</th>
<th>Instance</th>
<th>Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap</td>
<td>1 in²</td>
<td>0.468</td>
<td>0.946</td>
</tr>
<tr>
<td>Lap</td>
<td>1 in²</td>
<td>0.209</td>
<td>0.514</td>
</tr>
<tr>
<td>Angle Deviation</td>
<td>10 deg</td>
<td>0.396</td>
<td>0.860</td>
</tr>
<tr>
<td>Steering Radius</td>
<td>400 in</td>
<td>0.459</td>
<td>0.336</td>
</tr>
</tbody>
</table>

Figure 6.12 Feature Threshold Value table

![Graph representing gap defects](image)

Figure 6.13 Graph representing gap defects

Underneath the Feature-Threshold-Value table, the defect data is presented in a series of histograms. These graphs help visualize the distributions of the data to assist in selecting the best possible thresholds. The graphs can also be used to identify the threshold
by dragging the red line associated with the threshold. There is a graph for each defect that shows the amount and magnitude of the defect, such as in Figure 6.13.

6.6 MAJOR 2: DEFECT PRIORITIZATION AND RANKING

In Major 2, an operator will apply their expertise in deciding what defects are the most important to prevent. This section is dependent on the use case and different rankings for each defect may vary. Major 2’s layout is presented in Figure 6.14.

A series of default options streamline the matrix creation process if the operator wants to specifically target a defect type or wants to create their own custom rankings. By clicking any of the buttons the final rankings will automatically adjust to the choice selected. The three preset default options with their corresponding final rankings can be seen in Figure 6.15.
The AHP matrix works in the same way as described in 5.3. The user can click into any of the quadrants and choose the value they want to place. A quick example is shown in Figure 6.16.
The overall rankings are automatically adjusted according to the user preference to the rankings shown in Figure 6.17. Once the final rankings are finalized, scoring the ply scenarios can be performed in Major 3 to identify the best starting point and strategy combination.

6.7 MAJOR 3: PROPAGATION AND SOLUTION OPTIMIZATION

Major 1 has generated a normalized set of instance and severity measurements for each feature of interest. Major 2 provides a method for creating an overall ranking of many features with a series of pair-wise comparisons through the Analytical Hierarchy process. Major 3 combines the data into a single normalized score for each ply scenario. The lowest score will identify the best starting point and layup strategy of that iteration according to the thresholds and preferences used.

Figure 6.18 (a) Major 3 interface; (b) Multiple analyzed ply scenarios
Creating the array of starting points earlier will help the process planner as a variety of potential starting points can be easily compared to each other for each ply. The display for Major 3 can be seen in Figure 6.18.

The intuitive display clearly shows which starting points are the best by color coding them on a scale from red, being worst, to green, being best. When creating the next iteration of starting points, the CAPP module will select the starting point and strategy with the lowest score. Through multiple iterations the best scenario can be located with minimal effort.

The previous sections have presented a method for generating defect measurements and ranking the importance of these defects. Major 3 will use the findings from these two previous sections to give each starting point and associated layup strategy a score. The AHP scoring provides an objective function for comparing several different layup scenarios within the CAPP module’s ranking system and reflects on the importance as assigned by individual process planners.

To find the best starting point and layup strategy the program runs a procedure as follows. A localized grid of points is created near the center of the geometry over the whole layup. VCP will analyze the ply scenarios that were defined by the combination of grid points and layup strategy. Results are reimported to the CAPP, and each ply scenario is scored according to the AHP analysis and the defect measurement. Defects with higher weights have more impact on the ply scenario’s score, indicating higher amounts of that defect. The normalized scores, lower is better, can be used to select the best scenario. At this point, the current best can be used as is, or another round of iteration can be performed, using the previous best starting point and generating another starting point grid.
An example to illustrate how the CAPP module finds out the final score is presented in Figure 6.19 and Table 6.1.

![Figure 6.19 Final ranking from all measured features]

Figure 6.19 Final ranking from all measured features

<table>
<thead>
<tr>
<th>Defects</th>
<th>Threshold Percent</th>
<th>Ranking Percent</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap Instances</td>
<td>.468</td>
<td>.2</td>
<td>.0936</td>
</tr>
<tr>
<td>Gap Severity</td>
<td>.946</td>
<td>.2</td>
<td>.1892</td>
</tr>
<tr>
<td>Overlap Instances</td>
<td>.209</td>
<td>.2</td>
<td>.0418</td>
</tr>
<tr>
<td>Overlap Severity</td>
<td>.514</td>
<td>.2</td>
<td>.1024</td>
</tr>
<tr>
<td>Angle Deviation Instances</td>
<td>.396</td>
<td>.05</td>
<td>.0198</td>
</tr>
<tr>
<td>Angle Deviation Severity</td>
<td>.860</td>
<td>.05</td>
<td>.0430</td>
</tr>
<tr>
<td>Steering Radius Instances</td>
<td>.459</td>
<td>.05</td>
<td>.02295</td>
</tr>
<tr>
<td>Steering Radius Severity</td>
<td>.336</td>
<td>.05</td>
<td>.0168</td>
</tr>
<tr>
<td>Total Score</td>
<td></td>
<td></td>
<td>.530</td>
</tr>
</tbody>
</table>

The final score is found by multiplying the instance and severity percentages by the ranking percentages to find the overall score (Figure 4.21). The gap instances percent of .468 is multiplied by the gap rankings of .2 and then added on to the gap severity percent of .946 multiplied by .2 and so on until the final sum is found. By measuring the results of these different starting points and layup strategies an optimal scenario can be constructed.
for the process planners needs. The different scenarios can be easily compared, and an objective ranking of their selection criterion can be developed.

The rankings can be adjusted to favor combinations of properties that affect manufacturing or the original design constraints. For manufacturing, it would be important to primarily reduce the difficult to model defects imparted by fiber steering, and to avoid gaps and overlaps which could exaggerate into defects such as wandering tows. Heeding design constraints set forth by design for loading factors, such as the ply angle, material bulk, and void content are also essential. By highly valuing angle deviation, followed by gaps and overlaps, a more optimal set of layup parameters can be selected to remain true to the design parameters set forth by the laminates structural design and loading requirements.

6.8 CONCLUSION

The CAPP Software integrates many of the previously discussed defects and layup strategies to allow the process planner to seamlessly find the best starting points and layup strategies. After the initial setup in the CAPP software, the process planner can save hours of time that would be spent guessing and checking to find the best starting point. The defects are easily laid out before them and the graphs and charts intuitively display the information and rankings. By using multiple iterations, the process planner can pinpoint the best starting point on the layup.
CHAPTER 7
CONCLUSIONS AND FUTURE WORK

Process planning is a fundamental methodology that enables rapid manufacturing and certification of composite structures. This thesis presented a clear understanding of the process planning functions for AFP. These functions are tedious and require expert knowledge that is often not perpetuated. Moreover, these functions can profit from automation to enhance accuracy. Sixteen process planning functions were defined and illustrated. An industry survey provided to subject matter experts in academia and industry was performed, and detailed findings were tabulated. The perceived importance, automation and time requirements of the functions were discerned from the data and were ranked and grouped into functions of similar concept such as process optimization, toolpath optimization and miscellaneous.

7.1 CONCLUSION

In this work, a Computer Aided Process Planning software (Figure 7.1) has been developed. Additionally, a comprehensive list of layup strategies, fiber defects, and discrete process planning functions were cataloged and organized. The software was developed around these concepts of composite design and was specifically focused on the selection of layup strategies and their starting points. The automation of the software took place in a series of optimization iterations which developed ply scenarios based upon select layup strategies and recommended starting points near the surface’s geometric center. The
optimization used the resulting geometrical defects detected during virtual planning of the ply layups through VCP.

Figure 7.1 Snapshot of the CAPP Module

The workflow of the CAPP module was documented in a series of tutorials and demonstration videos (link to CAPP Demonstration). These resources were intended to bring a user with little knowledge of process planning up to a sufficient understanding to operate the CAPP module and the relevant batch processing functionality of VCP.

7.2 FUTURE WORK

Future work on the CAPP software would be the inclusion of additionally process planning functionality. The current state of the software focused on the set of geometrically detectable fiber defects, which represents a small subset of the defects set forth. A majority of the defects can have factors in not only the surface geometry, but sources such material imperfections, machine capabilities, and most importantly the processing parameters.
These parameters would include things such as compaction pressure, heating temperature, feed rates, and many others.

Incorporating defect detection models which utilize these other sources of information about the layup process, would enable much more of the process planning to occur before any manufacturing must be performed. Such a closed loop process in the process planning phase enables more rapid iteration of part design in order to account for the possible issues that may arise during manufacturing, where aspects such as material and machine operating cost must be considered.

7.3 SITUATION OF RESEARCH

The study of process planning in relation to composite manufacturing represents an overall goal of AFP research undertaken at the University of South Carolina’s McNair Center. This research complements path planning studies for AFP from structural points of view. These other areas of research attempt to optimize laminates not on geometrical defects, but how the placement and steering of fibers, such as in [65] and [66]. Other lines of research intend to expand on the fiber defect models to include geometry and material property effects such as in [68], which defines tow deformation during fiber steering.
REFERENCES


APPENDIX A

PROCESS PLANNING SURVEY RESULTS

Figure A.1 Graph of Function importance to process planning phase

Figure A.2 Graph of desired level of automation of each Function.
Figure A.3 Function Importance

Figure A.4 Time to complete function.
### APPENDIX B

## LAYUP STRATEGY PUBLICATIONS

Table B.1 Publication Timeline concerning layup strategies for the AFP process

<table>
<thead>
<tr>
<th>Year</th>
<th>Geometry</th>
<th>Title</th>
<th>Author</th>
<th>References</th>
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<td>1991</td>
<td>FLAT PANEL WITH HOLE</td>
<td>Use of Curvilinear fiber format in composite structure design</td>
<td>Hyer et al</td>
<td>[69]</td>
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<td>1996</td>
<td>COMPLEX SURFACE BUT CAN BE USED FOR ANY TYPE OF SURFACE CYLINDER</td>
<td>Design and manufacture of advanced composite aircraft structures using automated tow placement</td>
<td>Land</td>
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<td>1998</td>
<td>FLAT PANEL</td>
<td>Analysis and design of variable stiffness composite cylinders</td>
<td>Tatting</td>
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<td>2000</td>
<td>FLAT PANEL WITH HOLE</td>
<td>On the design, manufacturing and testing of trajectoryal fiber steering for carbon fibre composite laminates</td>
<td>Tosh et al</td>
<td>[70]</td>
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<td>2001</td>
<td>FLAT PANEL</td>
<td>Thermal Testing of Tow-Placed, Variable Stiffness Panels</td>
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<td>2002</td>
<td>FLAT PANEL WITH AND WITHOUT HOLE</td>
<td>Design and manufacture of elastically tailored tow placed plates</td>
<td>Tatting et al</td>
<td>[35]</td>
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<td>FLAT PANEL</td>
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