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Title:

Rapid Prototyping of Wind Tunnel Blade Geometry for Composite Manufacturing using Automated Fiber Placement

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Introduction:

The National Transonic Facility (NTF) at the NASA Langley Research Center, shown in figure 1, requires a set of 25 blades, shown in figure 2, to operate [4,5]. Due to the extreme wind speeds of this tunnel, any components that come loose during operations can have a devastating impact on the blades, likely rendering them unusable. The blades currently in use were produced by hand layup of fiberglass and, due to very tight engineering specifications, have taken up to a year of effort to produce each blade; therefore, these blades have a very high unit cost. The NTF currently does not have a full set of replacement blades. If a major incident occurred in the NTF, similar to a mishap that occurred in 1989, and due to cost and lead time to produce new blades, the NTF could be forced to shut down. Therefore, NASA is interested in an improved methodology for the fabrication of new blades.

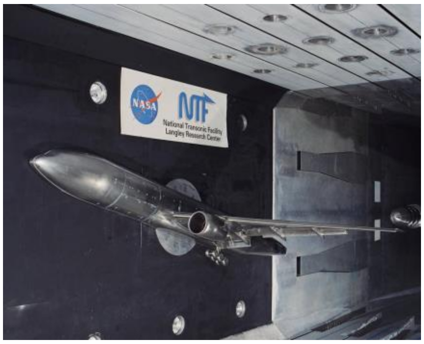

Fig. 1: NTF Facility.

Fig. 2: NTF Blade.

The alternative manufacturing process proposed by the NASA Preparing Researchers to Evaluate and Develop Impact–Driven Collaborative Technologies (PREDICT) project involves a hybrid of hand layup and robotic placement of materials. This methodology would utilize the Integrated Structural Assembly of Advanced Composites (ISAAC) robotic system for Automated Fiber Placement (AFP). ISAAC contains an Electroimpact (EI) robotic-arm-based fiber placement system, shown in figure 3, which places 0.25-inch-wide slit tape tows of carbon-epoxy material on flat or contoured surfaces. The first stage of developing this manufacturing process for wind tunnel blades required the design and

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fabrication of a representative shape as a proof of concept part. The complex, highly curved shape of the NTF blade posed significant challenges to fabrication. The focus of this paper is the design development activity for this blade shape including the programming and computer simulation of the fabrication process used to overcome these fabrication challenges.

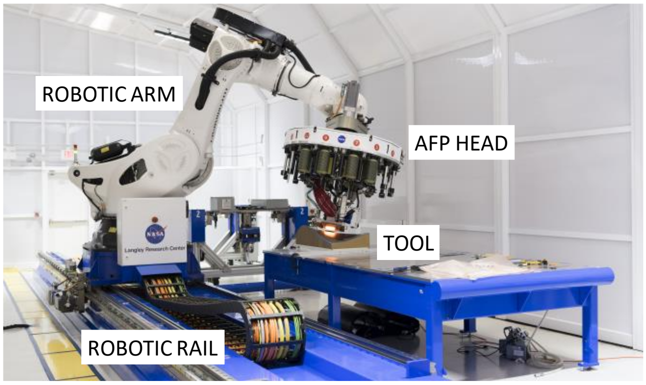

Fig. 3: ISAAC Facility.

Design Process:

The design process requires the establishment of the desired part shape, followed by an iterative approach to part design, tool position, programming, and simulation.

Blade Shape Reconstruction:

In order to program the material placement paths over the blade, a Computer Aided Design (CAD) representation of the blade's outer surface geometry was required. Unfortunately, a preexisting CAD model was not available, necessitating the development of a digital model from the geometry of the physical wind tunnel blade. This type of reconstruction process is necessary whenever a CAD model is not available, as is often the case for older and one-of-a-kind parts.

Since the project was to serve as an early proof of concept for the manufacturing process, the accuracy of the geometry compared to the physical blade was relaxed. Therefore, it was only necessary to construct a geometry that was sufficiently representative of the major features of the blade. The challenges of fiber placement on low-curvature surfaces are trivial, therefore the surface complexity at the root of the blade, where there is significant complexity, was the focus of the digital reconstruction.

The reference necessary for the surface geometry reconstruction were obtained by laying the blade on a flat reference surface and measurements were taken along each edge of the blade from this reference at constant increments, continuing from the tip to the base, allowing for the construction of the leading and trailing edges as individual splines within the CAD software. A ruled surface operation between the splines created the final representative surface for the digital blade. However, the digital blade's surface alone was not sufficient to continue to the machine programming. Additional surface and boundary definitions were necessary to perform the programming and manufacturing phases.

The boundaries represented the desired extent of the fiber coverage on the tool surface. Additionally, the quality of the AFP manufacturing was highly dependent upon the lead-in and run-out regions beyond the designated ply boundaries. Implementing these geometries with the blade model enables the creation of the final tool surface which would be physically created for AFP manufacturing. Figure 4.a represents the full tool surface geometry, where the blue lines represent the ply boundaries and lead in and run out regions beyond the boundaries. As previously stated, the flat geometry towards the tip of the blade had less potential for generating useful information for the project, so the tool surface was restricted to only include the blade root region with a small portion of the airfoil region.

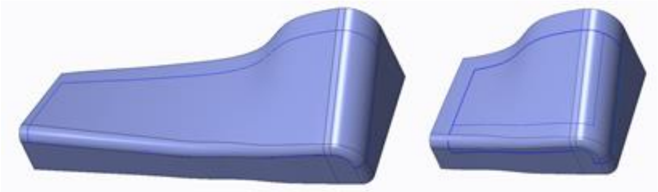

Fig. 4: (a) Full tool surface. (b) Partial tool surface.

With the completed digital tool-surface model, the process planning could be performed to evaluate the feasibility of manufacturing with the given tool surface geometry and machine configuration. If the following phases were successful, the layup tool would need to be designed to withstand compaction and bagging forces, then 3D printed at full scale from a high temperature thermoplastic to continue with dry-runs, final manufacturing, and composite curing cycles.

Tool Positioning for Coupon Table:

The position of the tool was driven by the available mounting positions in the work cell, and the results from the digital simulations of the VCP-generated G-Code. The ISAAC work cell (Fig. 3) contains the 6-axis EI robot on a linear rail which enables access to the coupon table, a 6-ft by 12-ft grid table adjacent to the rail, and a controllable rotator. While fabrication on the rotator would have afforded additional flexibility in programming, the tool was mounted on the coupon table for the PREDICT activity to reduce fixturing and material cost, and to meet the deadline of completing fabrication by the end of the four-month PREDICT activity. The tool model was initially positioned at the midpoint of the table away from the rail to provide an initial starting point for programming.

Process Planning:

Process planning represents the joining of material properties, rules of composite design, and the available manufacturing resources. Combining these sets of knowledge enables the development of machine code to efficiently produce the composite laminate with the desired physical characteristics.

ISAAC uses the composite manufacturing planning software Vericut Programming (VCP) and Vericut Simulation (VCS) for fiber placement operations [1]. VCP generates a series of numerical control (NC) files that completely control the robot throughout the material placement, or layup, process. These files encode data for head position and orientation for on- and off-part motions, feed rates to control the flow rate of composite tows, and heating parameters that ensure proper adhesion between the current ply and the substrate. To begin programming, a set of fiber orientations must be defined for each ply. Additionally, a starting point and a layup strategy must be chosen within the ply boundaries of the CAD model. The layup strategy represents the method used for generating material paths over the surface for each course of the ply. The starting point defines the initiation point for the propagation of the layup strategies [3] to minimize AFP defects [2].

To develop the NC code for the blade, a fiber orientation sequence which favored paths along the length of the blade was chosen, as this sequence would most effectively withstand the centrifugal loading of the blades. The Natural Path method, one of layup strategy options provided by VCP, was selected for its ability to achieve sufficient coverage on complex surfaces. Starting points were selected iteratively until the coverage had no significant generation errors, and partial courses were minimized. By programming for the 0.25-inch-width tow material with four tows per course, the coverage depicted in Figure 5.a was generated.

The next step in using VCP involved connecting the paths between the courses and the off-part motion and defining the feed rates of the robot's motion. Additional parameters involving the motion of the robot were also defined during this stage and were essential to reducing simulation errors encountered during VCS testing. A planar safety zone was defined about the surface of the tool which served as the retraction zone between each course. A feed rate of 1000 in/min was defined for on-part motion and 1500 in/min for off-part motion.

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The ISAAC robot runs along a linear rail which provides an additional degree of freedom. By utilizing the linear rail, a much greater portion of the coupon table work area becomes kinematically accessible. Without the rail, issues such as tool collisions, joint limit errors, and kinematic singularities are much more common. The options available through the VCP post-processor for ISAAC, enable the offset of the rail position, from the current tool tip position (X). This offset may be programmed as a constant, or an interpolated value between a set of X values. The offset can be controlled differently at each point of the motion path by introducing specific instructions at the desired update zone. The blue lines of Figure 5.b depict the off-part motion, and the arrows represent the start and end points. The blue sphere is where special instructions were inserted to enable different values of the offset between the rail and the current tool tip position.

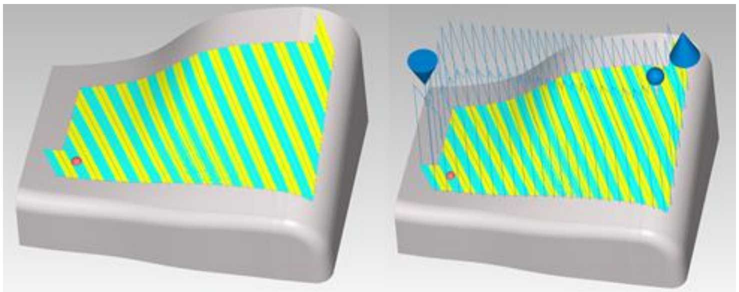

Fig. 5: (a) Courses generated within the ply boundaries. (b) Off-part motion connecting course paths.

Once courses, off-part motion, and machine specifications are programmed, the program can, in theory, be sent directly to the robot to commence the layup. However, the presence of errors is likely for new programs on new complex tools. Therefore, the use of a robot simulation software enables the programmer to rapidly find errors and update the relevant parameters in VCP to create a better NC program.

VCS Simulations:

To begin simulating the blade fabrication program, the virtual work cell was loaded. Additionally, The CAD tool was loaded onto the coupon table allow the software to check for collisions. VCS provided several useful tools for detecting, and subsequently investigating, issues arising during simulation. The key issues encountered during testing of the blade program were joint limit errors and heater collisions. Joint limit errors would arise when the robot could only reach a position by exceeding the allowable limits set for each joint. Similarly, heater collisions would occur when the path of the layup did not have a valid orientation to avoid the edges of the heater impacting the tool or coupon table.

The joint limit errors and heater collisions stemmed from the relative positioning between the robot base and the tool location on the coupon table, along with the parameters defined during the programming of the NC file. Repositioning the tool on the coupon table was the first step in resolving these problems since it provided the coarsest level of optimization for error reduction. Testing with tool positions on the front, back, left or right of the coupon table, in addition to the angle of the tool from the rail was conducted. Inspection of each of these positions and a knowledge of valid joint positions enabled the selection of a final position on the coupon table. The best position selected during this phase would eliminate extreme joint errors and heater collisions.

Further elimination of errors would come through the fine tuning enabled by the previously mentioned machine parameters. Increasing the offset (labeled as E1 on ISAAC), which represents the delta between the robot base and tool tip, enables the robot to share movement more between its axes as opposed to relying on fewer joints. By sharing these movements, joint limit errors can be significantly reduced. Additionally, leaning the heater forward and backwards enables control over heater collisions that occur in surface regions of high curvature on the tool.

Each time a parameter or position is updated to improve the simulation, a new NC file must be generated through VCP and rerun in VCS. By updating the file, it is possible that changing a variable to fix one issue may generate an entirely new issue. The back and forth between issues and fixes are not common simple tool paths, but for complex shapes such as the blade, several iterations may be necessary to develop a final successful NC file.

In this case, the primary challenge arose during the programming and simulation cycle as a result of the current robot and tool configuration. Due to the width of the heater assembly, specific regions in of the blade are unreachable as a result of the double curvature of the part surface. It was not possible to alter the lean of the heater within reasonable constraints to avoid the collisions that occurred.

Several solutions present themselves for the heater clearance issue. The simplest involves a redesign of the tool and blade to an alternative shape which features less curvature, eliminating the areas of collision. A new heater may also be sourced which has a smaller collisions box, allowing for manufacturing of the currently designed tool.

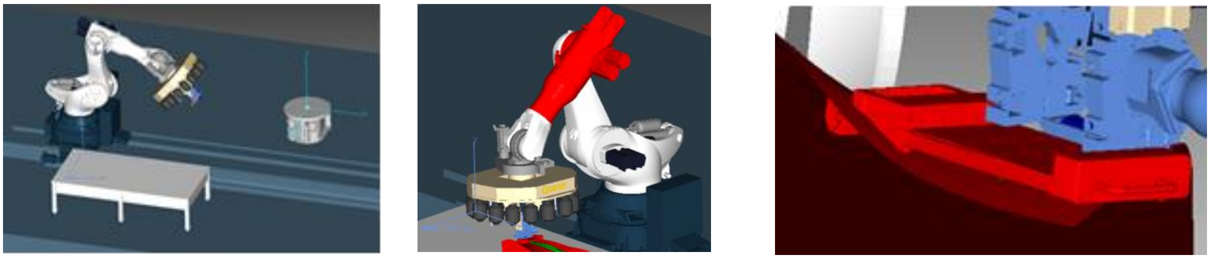

Fig. 6: VCS simulation screen captures including (a) VCS Simulation Environment. (b) Joint error on Axis 3. and (c) Heater/Tool Collision.

Conclusions:

The goals of the rapid prototyping process were to build a CAD model to represent the wind tunnel blade, develop a stacking sequence and program the laminate, and ensure the validity of the resulting NC files through simulation. Unfortunately, collision errors proved to be unavoidable with the current configuration of the heater on ISAAC, so the designed part could not be fabricated during the PREDICT activity. An alternative shape for the manufacturing demonstration part will be presented in the proposed paper.

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