CREATION OF A DIGITAL TWIN FOR AUTOMATED FIBER PLACEMENT

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ABSTRACT

Automated Fiber Placement (AFP) is a manufacturing process used to produce large, lightweight composite structures at high rates and increasing reliability. Currently, the process is black box where paths and process parameters are sent to the machine, and it is trusted to maintain the correct values. There are limited methods of monitoring real time process parameter values for current and future analyzing. Even when the exact same parameters are used on the same part multiple times, the resulting manufacturing quality can differ largely. This report will discuss the creation of a digital twin with the capability to simulate and monitor the entire AFP process. A digital twin will provide the ability to examine the process in real time, in addition to after the process is completed. The data collected will then be compared to expected data to examine any differences. Analysis of each point during manufacturing will lead to a deeper understanding of AFP.

Keywords: Digital Twin, Project Lifecycle Management, Industry 4.0, Automated Fiber Placement
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1. INTRODUCTION

1.1 State of the Art

Rapid developments in technological capabilities in recent years have enabled the marriage between virtual models of complex physical systems and their real-world counterparts. Digital Twin (DT) is a term that embodies this integration of data between the virtual and physical realms. While not at full scale, portions of DT technologies are currently utilized in various industries to enhance existing product lifecycle management (PLM) tools. PLM tools create a system that allows companies and organizations to monitor the progression of a product, beginning from ideation, to manufacture, and ultimately finishing at the product's end of life. In the composites industry today, the activity of PLM is more difficult due to the inherent complexity of a PLM system and the disconnect of information from the phases of PLM. There have been some successes at developing portions of a DT for the composites industry PLM, however no attempts at creating a DT for the entire PLM cycle were found in the available literature [1] [2] [3] [4] [5]. This gap can be understood through the context of the definition of the term Digital Twin. A general definition of a Digital Twin is given as: "*An integrated, multiphysics, multiscale, probabilistic simulation of an as-built system that uses the best available physical models, sensor updates, product history, etc., to mirror the life of its corresponding twin* [6]." Based on this definition, the foundational components of a DT consist of three things: (1) a physical model, (2) a virtual model, and (3) the data connecting them [7]. The linking between these three features demonstrates that a DT is not a precocious all-in-one model, but a cutting-edge interconnection of data between the virtual and physical domains. The linking of the lifecycle data into a comprehensive virtual system enables accurate, data backed predictions of the physical product by the DT to enhance significant components of the PLM, such as product design optimization and development of manufacturing systems [8] [9].

1.2 Goals of an AFP Digital Twin

The target of this research is to create a complete DT of the entire AFP manufacturing process. This includes, but is not limited to, post processing of initial design, monitoring and inspecting data from the design, design process planning, manufacturing, and post-production phases. The software selected for development of this DT model was Tecnomatix Process Simulate (PS) by SIEMENS. Process Simulate was chosen as the tool for building the DT system due to its robustness and accuracy as a simulation environment, as well as a number of reporting tools that simplify data acquisition and analysis. In addition, the Process Simulate Application Programming Interface (API) was useful in allowing the researchers to integrate the simulation environment with other tools, such as path planning and post processing routines. Process Simulate provides many tools required to build a DT model. Among these are 3D simulation and editing, collision detection, joint monitoring, and data communication. These abilities allow for programming and simulation of the AFP process, all within a single software suite, on any CNC controlled AFP machine. Additionally, all pertinent process parameters that can be streamed from the AFP machine CNC controller will be directly input real-time into Process Simulate, creating a real-time digital model of the manufacturing process. Furthermore, data from external partner software programs such as process planning [10] and inspection [11] will be integrated into Process Simulate. This data will be used to produce a further enhanced DT from the design phase to the end of manufacturing. The data can then flow freely between all phases of the DT to improve the overall product lifecycle. The expected data flow is presented below in Figure 1.

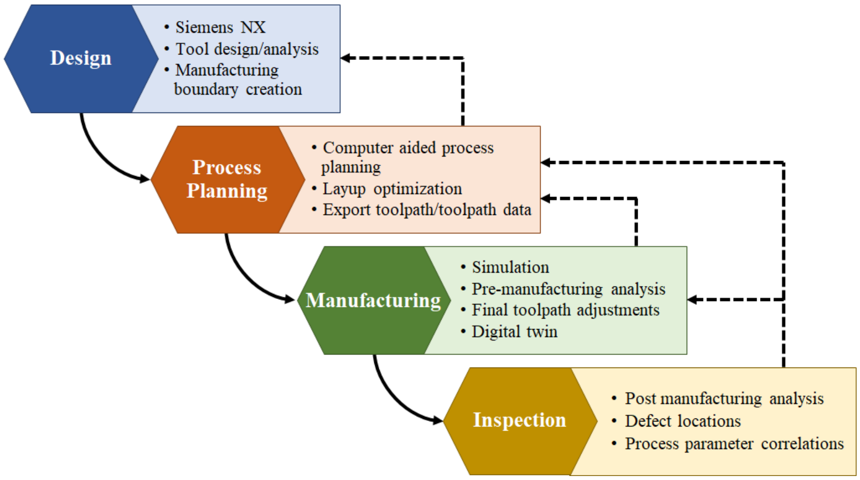


Figure 1: Diagram of data flow within the virtual manufacturing model

1.2.1 Virtual Commissioning

An additional goal of this project is to allow for "Virtual Commissioning" of the entire AFP system. Virtual Commissioning (VC) as described in [12] refers to the partial digitization of the commissioning process for traditional manufacturing systems. More specifically, VC refers to the integration of both kinematic and logical components of a cell in one unified simulation, such that automation code on both robots and programmable logic controllers (PLCs) can be validated against the virtual model before implementation on the physical system. This VC approach can drastically reduce the amount of time required to launch a manufacturing system, in addition to time reduction for making changes to an existing system.

AFP systems are rarely a single machine that performs exactly as programmed, and as such VC is applicable to these systems. An AFP manufacturing cell may contain both a layup system and a robotic inspection system, or such a system may contain multiple robots performing layup simultaneously. Other components like additional actuators, axes, sensors, and inspection devices can also be integrated. The introduction of VC to this type of system allows engineers to test the integration of these various components of the cell using a virtual model before they are implemented. This high level of fidelity in the simulation model is a target of the DT system.

2. EXPERIMENTATION

2.1 Building a Digital Twin of AFP

In order to create an accurate Digital Twin of the AFP manufacturing process, existing CAD models and software were referenced and imported into the Process Simulate model. The University of South Carolina McNAIR Center is an Advanced Composites research facility equipped with a Lynx Horizontal AFP machine by Ingersoll Machine Tools (IMT). For this reason, the McNAIR Center's AFP manufacturing cell was used as the target model for the DT. The first step to create the Digital Twin of the IMT AFP system was to import a CAD model and construct a kinematic tree of the AFP machine. This model, shown in Figure 2, was based on CAD geometry developed by IMT. Elements of the assembly were associated with "links" that describe groups of components that move together as a single unit in context of the machine's kinematic tree, as shown in Figure 2. These links were then connected with "joints" that represent how the links can move with respect to each other. This movement is specified using an axis and can be either prismatic or rotational. The exact joint location, limit, velocity, and acceleration parameters were set to IMT specifications. These specifications were included in a separate file called “motionparameters.e.” This file is associated with the DT model and instructs Process Simulate how to emulate the motion of the machine. Frames were defined at the tool center point (TCP) of the roller and the origin of the machine as specified by IMT. A frame is a location including both the cartesian and the rotational component of the location. The TCP frame allows location of the roller on the machine relative to the origin frame of the machine.

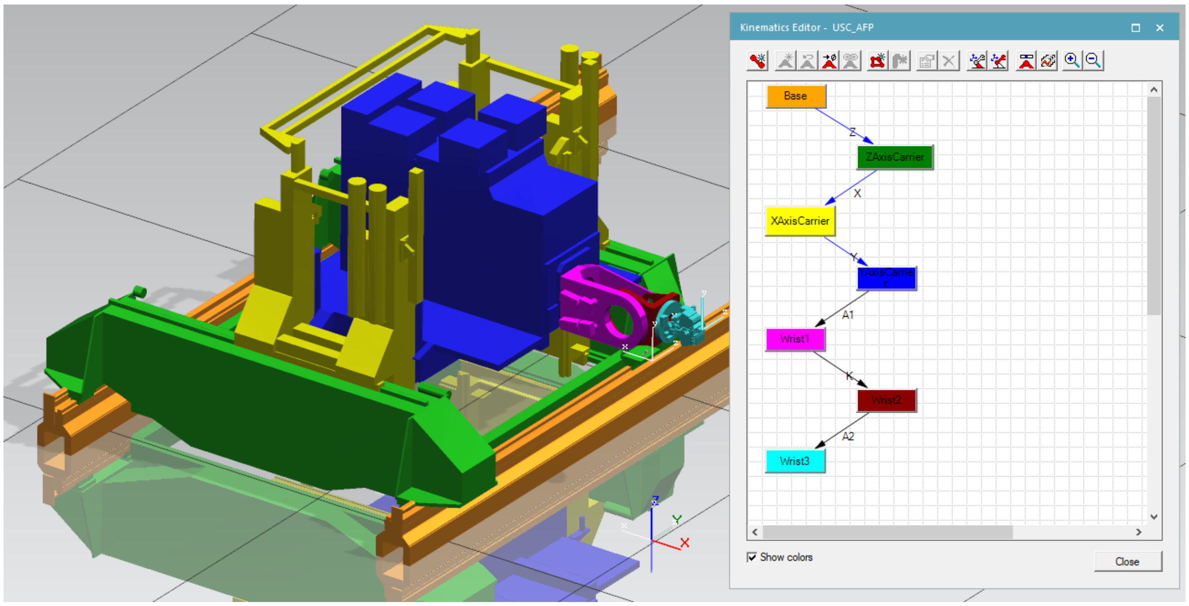


Figure 2: The kinematic model of the AFP machine inside of Process Simulate.

The machine’s mandrel and tool were then added to the DT environment, using the same procedure as described above. The tool was located on the mandrel based on the mounting locations used on the actual machine. The mandrel was then added as an external axis to the AFP system. The resulting system is shown in Figure 3.

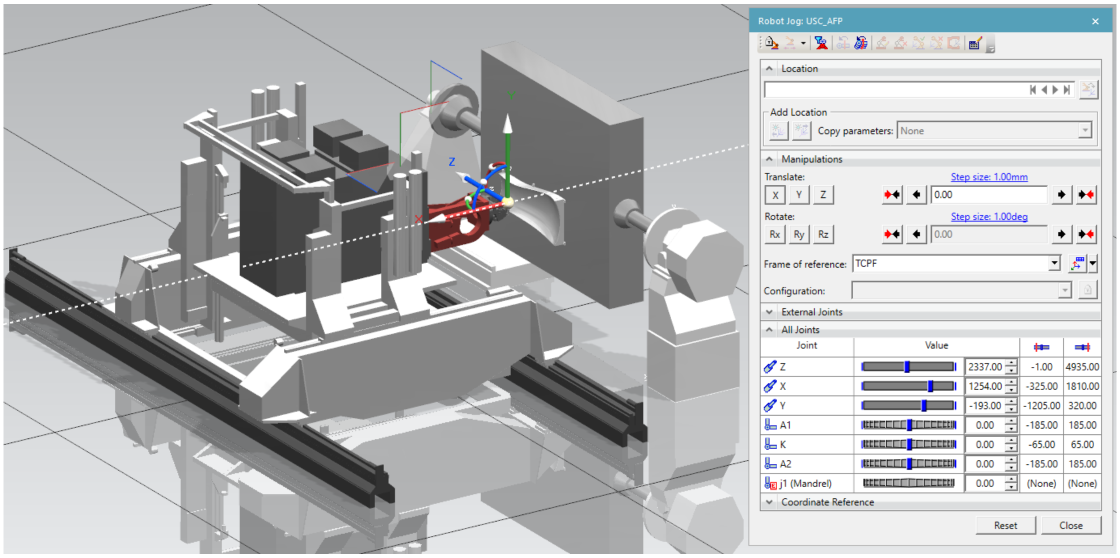


Figure 3: The finalized kinematic model for the AFP system and mandrel. The right shows the joints of the machine and their limits, as well as the external axis

To further improve the accuracy of the DT environment, additional components in the cell were modeled. The rail mounted robotic inspection system and fencing that are present in the physical cell were added to the simulation model. The CAD and kinematic models for these components were available directly from an existing library of resources distributed with Process Simulate. These components were loaded into the cell and placed in their correct locations based on the physical cell. Adding these additional components allows the engineers to assess their layup strategy in the context of the entire cell, considering possible collisions with the surrounding equipment, or to evaluate integration with the inspection system. The completed cell layout can be seen in Figure 4.

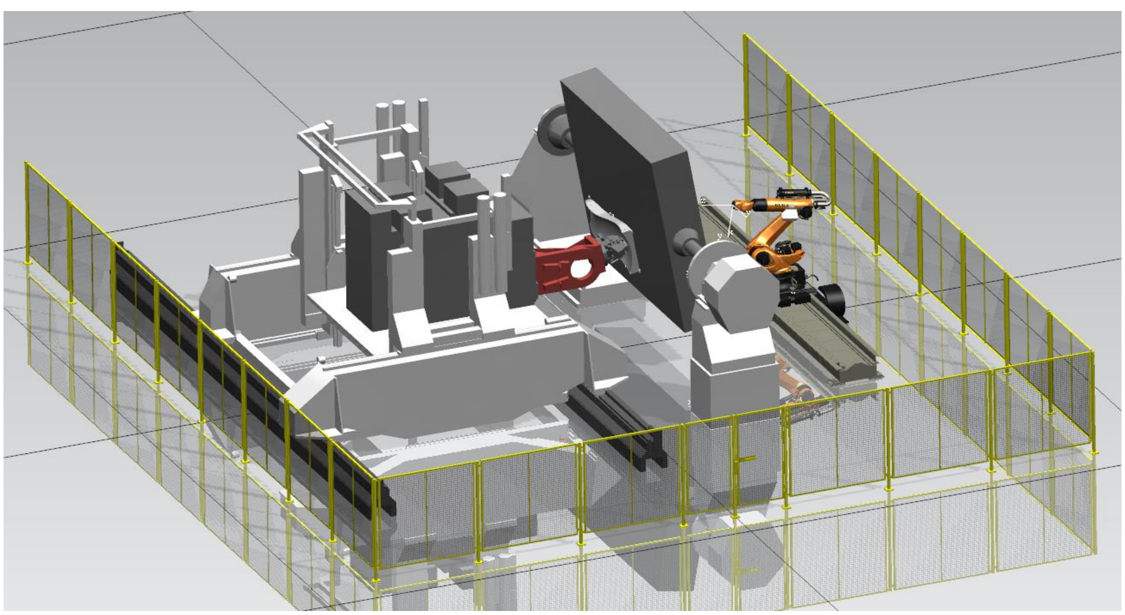


Figure 4: The completed Digital Twin cell layout

1.1.1 2.1.1 Kinematic Simulation

After the DT layout was complete, basic kinematic simulation could be performed. The IMT Lynx has a total of 7 axes, designated as X, Y, Z (prismatic), A1, A2 (rotary), K (wrist), and C1 (mandrel rotary). The inverse kinematic solver implemented within Process Simulate was used to solve axis positions for the AFP machine, given a TCP location. This functionality was tested using the "Robot Jog" and "Jump to Location" tools to verify Process Simulate would properly solve for joint values based on cartesian input (Figure 5).

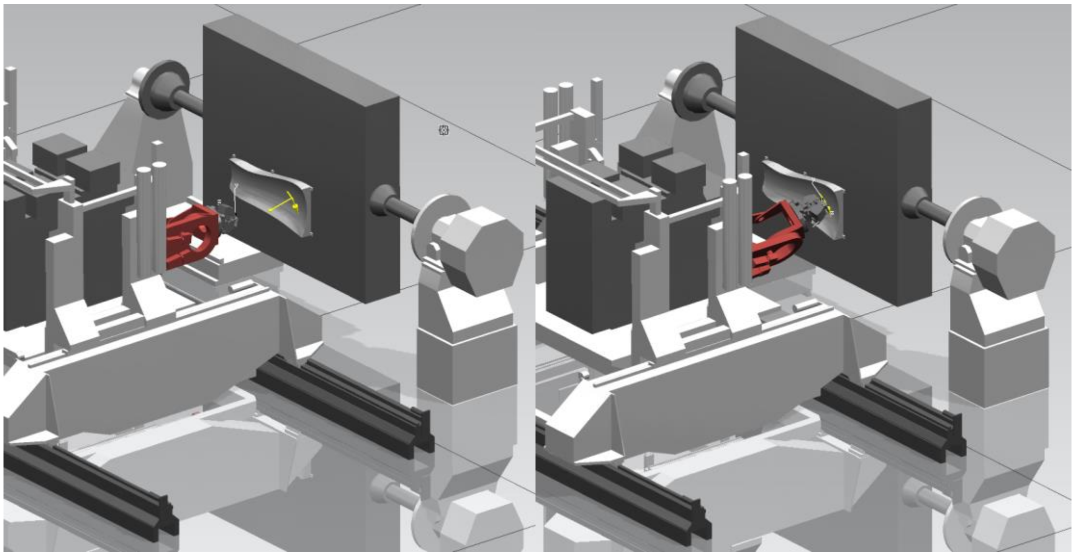


Figure 5: Verification of the inverse kinematics solver inside Process Simulate. The images depict "jumping" the AFP machine to the target location

Due to the inherent nature of the kinematic chain of the IMT AFP machine, there are possible ambiguities in this inverse kinematic solver. This is shown in Figure 6, which depicts two possible solutions for the same target location.

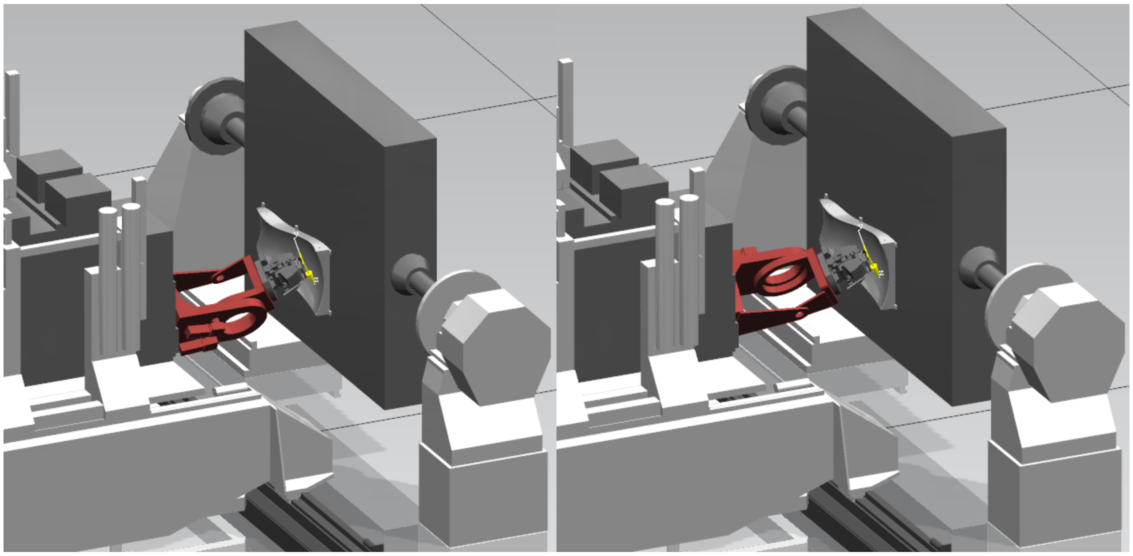


Figure 6: Two different kinematic solutions for the same target location

When programming this machine, engineers need a way to specify the kinematic solutions they wish to use for the layup. In order to allow this specification, the "**motionparameters.e**" file associated with the AFP model was altered to include syntax that differentiates the solutions based on the joint values of A1 and A2 (the primary and secondary rotary wrist joints). This ensured a unique classification of kinematic solutions and allows the user to specify the best solution for their needs. Process Simulate uses this information to present these solutions to the user as options during path planning.

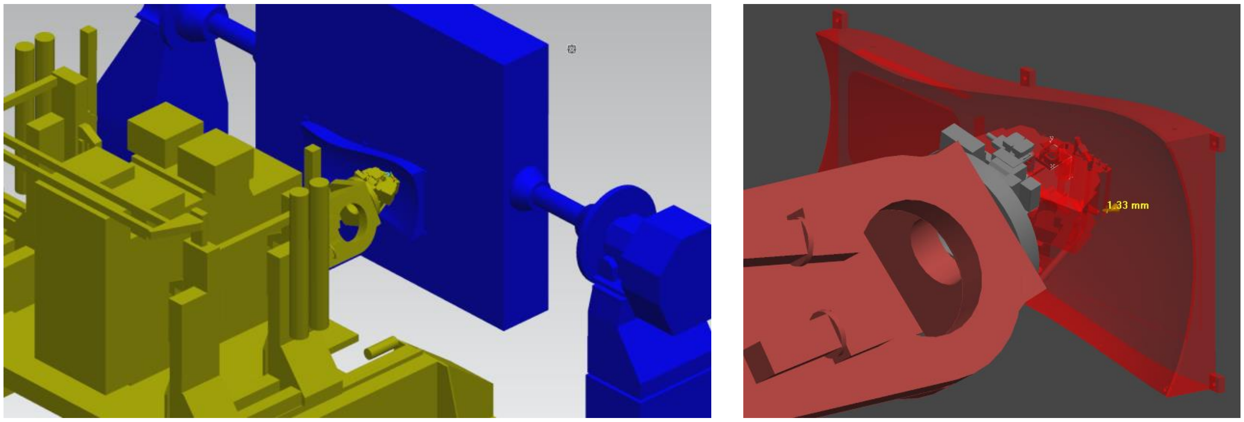
1.1.2 2.1.2 Path Planning

Two workflows were proposed to generate the required course paths for simulation and eventually programming purposes. The first methodology uses an external path planning software developed by IMT called iCPS to generate course center line definitions as a series of coordinates defined relative to the tool surface. These definitions were exported from iCPS in their native format. The Process Simulate .NET API was then used to build a tool inside of Process Simulate to load this series of points as a continuous robotic operation that could be executed by the kinematic model inside Process Simulate. The paths were then verified inside of Process Simulate, external axis positions were set using built in tools inside of Process Simulate, and robot configurations were set to avoid any potentially anomalous kinematic solutions. The paths could then be simulated and checked for any potential layup problems, such as collisions, rapid axis accelerations, discontinuities, etc.

A very similar process was followed for our other proposed workflow. In this case, the design of the toolpaths was performed entirely inside of Process Simulate by using the Continuous Process Generator (CPG). The CPG tool inside of Process Simulate allowed us to create a continuous coverage pattern over the surface of the curved tool with even spacing of courses at a defined angle. These courses were then analyzed in much the same method as described above, using the built-in tools inside Process Simulate to set external axes and configs, and then testing using kinematic simulation and collision detection. This process was more useful for rapid iteration and testing, and likely would not be employed for actual composite path programming. The final proposed process would involve path planning performed in an external tool and then loading the course centerline definitions into Process Simulate as described above.

3. RESULTS

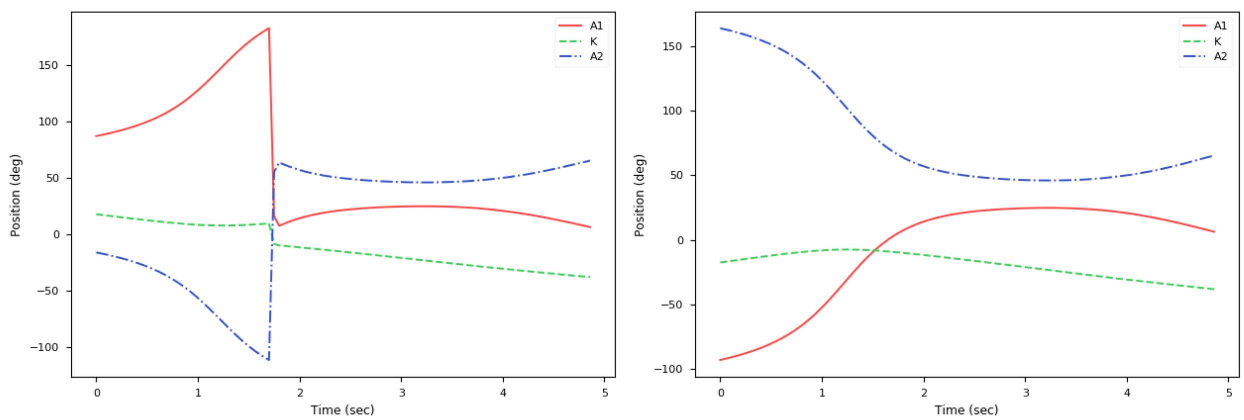
The current state of the virtual AFP cell can be seen in Figure 4. Using this model, we can monitor aspects of the layup such as collisions, joint values, layup time, and velocity profile which can then be used to identify potential manufacturing problems. From the images presented in Figure 7, it is shown that a collision set has been defined between the AFP machine and the mandrel with the attached tool. A collision was detected through layup simulation, and Process Simulate displays this collision by highlighting the 2 colliding parts and providing the penetration distance (1.33 mm). Once a collision is detected, the user can directly edit the path in question or select a different kinematic solution method.



(a) (b)

Figure 7: (a) Emphasized collision set and (b) an identified collision with penetration distance

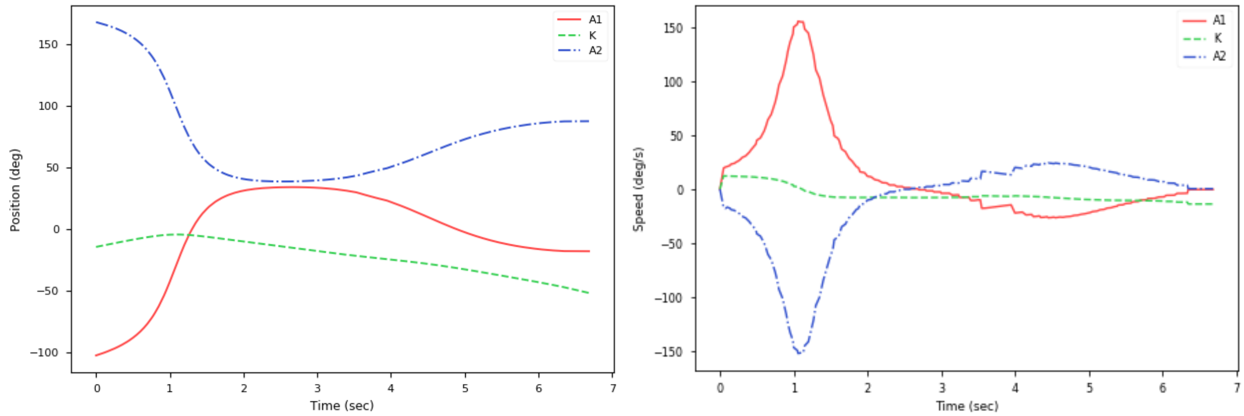
Similarly, Process Simulate can monitor joint positions and velocities and display graphical analyses before manufacturing. Figure 8.a presents data that shows instantaneous large axis movements during a course. These movements are typically caused by the machine passing through a singularity or a kinematically restricted point. Through adjustment of the kinematic solver technique, the axis movements presented in Figure 8.b can be achieved. These changes are usually made prior to pushing the program to the machine because an instantaneous movement such as the one presented can damage the machine.



(a) (b)

Figure 8: Graphs showing the radial axis position over time for a course (a) with and (b) without a large position jump

Another potential problem during manufacturing is a rapid axis movement (Figure 9) which can cause defects if not resolved. Such an issue is normally noticed through careful observation of a simulation. Again, using joint analysis within Process Simulate, the user can immediately notice a rapid change in position and velocity and adjust accordingly. These tools allow for a deeper knowledge of the machine's activity throughout a manufacturing process and can prevent defects. Correlation of this data with actual manufacturing data assists in better programming of the AFP courses.



(a) (b)

Figure 9: Graphs showing the (a) position and (b) speed of a course with a rapid axis movement

4. CONCLUSIONS

4.1 Conclusion

Process Simulate is an extremely powerful and robust software suite which allowed the initial steps in the creation of a Digital Twin for the McNAIR IMT Lynx AFP machine. Within this paper, it is clear that a full Digital Twin should not only emulate actual machine performance and characteristics via rapid data transfer but be capable of monitoring and solving issues that occur when commissioning a manufacturing cell. With accurate models for both machine geometry and kinematics, it was shown the Digital Twin can emulate any item within a 3D environment. Tools within the Digital Twin give the user the ability to make rapid developments and changes in the function and simulation of the machine, thus reducing down time and increasing efficiency of all aspects of PLM. This optimization of the PLM via integration of the Digital Twin is a necessity of manufacturing within Industry 4.0.

4.2 Future Work

In this paper only a small portion of the capabilities of Process Simulate were utilized. Future work on the Digital Twin will lead to enhanced cell integration, including modeling of the robotic inspection system in the same manner as the AFP machine. With the inclusion of manufacturing and inspection simulation in the Digital Twin, the entire cell can be commissioned as one, unified environment, allowing further optimization of machine use. Movements of the inspection system will be able to be coordinated with the AFP machine. This is a very important aspect of the Digital Twin, as it will allow for virtual retrofitting of standalone inspection systems into in-process inspection.

Additionally, the Digital Twin allows for integration of software from external partners, with one example being machine tool path optimization. This software will be implemented for optimized path validation against the original model, and lead to a drastic reduction in unnecessary machine travel. Further augmenting this ability will be a proprietary machine learning algorithm, which will input data analytics streamed from Process Simulate into a neural network, allowing the system to make predictive models for machine movement optimization. With the implementation of neural network machine learning coupled with tool path optimization, the Digital Twin may potentially lead to the capability of semi-automated process planning for Automated Fiber Placement.

5. REFERENCES

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