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Machine Learning Approach for Optimization of Automated Fiber Placement Processes


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Abstract

Automated Fiber Placement (AFP) processes are commonly deployed in manufacturing of lightweight structures made of carbon fibre reinforced polymer. In general, AFP is connected to individual manufacturing knowledge during process planning and time consuming manual quality inspections. In both cases, automatic solutions provide a high economic potential. Therefore, a machine learning approach for planning, optimizing and inspection of AFP processes is presented. Process data from planning, CNC and online process monitoring is aggregated for the documentation of the part specific manufacturing history and the automated generation of manufacturing knowledge. Within this approach a complete automation of data capturing, data storing, modeling and optimizing is achieved.

Keywords: machine learning; assisted process planning; process data visualization

1. Introduction

1.1. Motivation

Especially in aerospace applications, lightweight structures are becoming increasingly important aiming to reduce the fuel consumption. Therefore, modern wide-body aircrafts like Boeing 787 [1] or Airbus 350XWB [2] consist of more than 50% composite materials by weight, especially carbon fiber reinforced plastics (CFRP). Due to the high strength-to-weight ratio compared to conventional aircraft materials, the relative share of structural parts is up to 80% by volume. Such integral constructed parts are characterized by huge dimensions and high unit costs. For this application, the Automated Fiber Placement (AFP) process evolves into one of the leading manufacturing processes in lightweight design. This process combines high productivity with high quality. Within this process, several pre-impregnated carbon fiber slit-tapes are laid-up by a fiber placement head on a tooling surface side-by-side simultaneously. During the lay-up process, certain defects may occur. They can be divided in four categories:

- Positioning defects (gaps, overlaps, missing tows, twisted tows)
- Bonding defects (bridging, air pockets)
- Contaminations
- Tow defects

Today, AFP processes are distinguished by a high amount of manual interventions in process planning, process and quality assurance (QA). As an example, the quality control during AFP processes is manually done by visual inspection of the operator. In this time, the lay-up process has to be interrupted. The visual inspection and the potential repair process in cases of detected defects are done for every single ply during the AFP process and are therefore very time-consuming.

In the AFP process, pre-impregnated carbon fibers (tows) are placed automatically on a tool surface. Due to recent technological advances in the production technology, increasingly complex parts can be realized. However, this
process also entails a higher complexity of the tools and tool surfaces. Regardless of existing CAD-CAM applications, the additional high structural requirements for CFRP laminates demand a manual, time-consuming adaptation of the laying paths while adhering to strict design rules. In addition to the selected tow paths, the process parameters have a decisive influence on the laying quality. Inadequately pre-heated tool surfaces or deviating compaction pressure can lead to defects, such as surface-dissolving tows. If existing errors are not detected and corrected, deviations from design and structural requirements of the component occur. As a consequence, the machine operator is responsible for quality assurance, which is related with a time-consuming visual inspection of the individual layers. This approach not only restricts the productivity of the AFP process, but also entails high repair costs for undetected errors, which need to be corrected at a later stage, or in exceptional cases can lead to the rejection of the entire component.

1.2. Monitoring and optimization of manufacturing processes

As Soucy showed, a camera system mounted on the fiber placement head can support the operator during machining [3]. This enables the operator to inspect continuously the lay-up of fiber tapes. However, this approach is not corresponding to an online process monitoring, because of the high demands on cognitive abilities of the operator. Today, automated visual monitoring systems are not common due to the high demands on illumination and image analysis [4]. Nevertheless, several visual monitoring approaches were developed. As an example, Miene showed an algorithm for the calculation of the fiber orientation for single rovings during the manufacturing process of carbon fiber reinforced plastics (CFRP) for the prognosis of occurring defects. Disadvantages of this approach are the time-consuming numerical image analysis and the ambient conditions depending reliability [5]. A different approach is the using of laser triangulation sensors for the monitoring of single tows. The monitor system is able to localize the position of the tows by an edge detection [6]. In the field of quality control of fiber-reinforced components the use of ultrasonic probes is prevalent after the manufacturing process [7].

Several machine learning approaches are presented for different manufacturing applications. For metal cutting processes an overview on applied optimization techniques are given in [8] and [9]. In recent research evolutionary optimization algorithms, particularly Genetic Algorithms (GA), Simulated Annealing (SA) and Particle Swarm Optimizing (PSO) are focused [9]. Nevertheless, the correlations between process parameters and their effects are not modelled by these algorithms, because a model for the optimization process was not required in the given application. Therefore, the determined process parameters were only applicable for the given process with a restricted set of boundary conditions. For milling processes, a method based on a support vector machine as a machine learning approach to model the obtained process data was shown. By using a numerical optimization of the model, optimal process parameter could be determined to minimize machining time and satisfy given boundary conditions. Due to the complete automation of data capturing, data storing, modeling, optimizing and machining, a self-optimizing cutting process was achieved [10] and [11].

### Nomenclature

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AFP</td>
<td>Automated Fiber Placement</td>
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<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
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<tr>
<td>CAM</td>
<td>Computer Aided Manufacturing</td>
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<tr>
<td>CFRP</td>
<td>Carbon Fibre Reinforced Plastics</td>
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<td>FPA</td>
<td>Focal Plane Array</td>
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<td>IR</td>
<td>Infrared</td>
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<td>NC</td>
<td>Numerical Control</td>
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<td>QA</td>
<td>Quality Assurance</td>
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<td>RA</td>
<td>Regression Analysis</td>
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<tr>
<td>SVM</td>
<td>Support Vector Machine</td>
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<tr>
<td>$T_H$</td>
<td>Heater temperature</td>
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<tr>
<td>$v_{AFP}$</td>
<td>Lay-up velocity</td>
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2. Approach

2.1. Idea

The basic idea of the presented approach is a continuous data storage and usage over several steps of the process chain. In the first step, the AFP process is planned by using the currently best known process parameter. In the next step, all relevant information of the planning process is used for the parameterization of the process monitoring system. As an example, the placement path is extended by correlating planned gaps and tolerances. During the manufacturing process, the online monitoring system is able observe the process and to classify detected anomalies based on planning data. In addition, all process information from planning, the machine control and the monitoring system are aggregated in a database. Afterwards, the manufacturing data can be used in two different ways. On the one hand the detected defects and anomalies are visualized during QA to support the operator. On the other hand, the aggregated data is analyzed by machine learning methods for optimization of process parameters of future processes. The described approach is schematically shown in Fig. 1. In the following, the mentioned modules are described in detail.

![Fig. 1. Approach of data aggregation based process optimization](image-url)
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