Towards a model-based control for thermoplastic automated fiber placement

Lars Brandt, Johannes Wüstner, Dominik Deden, Michael Kupke, Christoph Ament

Angaben zur Veröffentlichung / Publication details:

Brandt, Lars, Johannes Wüstner, Dominik Deden, Michael Kupke, and Christoph Ament. 2024. "Towards a model-based control for thermoplastic automated fiber placement." *Manufacturing Letters* 40: 97–99. https://doi.org/10.1016/j.mfglet.2024.03.021.

Manufacturing Letters 40 (2024) 97–99

Contents lists available at ScienceDirect

Manufacturing Letters

journal homepage: www.elsevier.com/locate/mfglet

Full Length Article

Towards a model-based control for thermoplastic Automated Fiber Placement

Lars Brandt [a,*], Johannes Wüstner [b], Dominik Deden [a], Michael Kupke [a], Christoph Ament [b]

[a] German Aerospace Center (DLR), Center for Lightweight Production Technology, 86159 Augsburg, Germany
[b] Augsburg University, Chair of Control Theory, 86159 Augsburg, Germany

ARTICLE INFO

Article history:
Received 15 February 2024
Accepted 19 March 2024
Available online 2 April 2024

Keywords:
Carbon Fiber Reinforced Composites (CFRP)
Automated Fiber Placement (AFP)
Control Systems
Model Predictive Control (MPC)

ABSTRACT

Commercial aviation must become climate neutral in the next decades, a key factor are lightweight fuselages that may increase fuel efficiency of an aircraft over its lifetime. New manufacturing processes such as in-situ, thermoplastic Automated Fiber Placement (AFP) enable larger and more complex carbon fiber reinforced components. In order to increase material performance process parameters, have to be controlled precisely. A sensible approach is introduced in this work by implementation of Model-Based Control (MPC), which can accommodate for process specific challenges. A finite element model of the process is designed and integrated in to the control. Subsequently, layup trials validate the improvements and thus show the potential of the control approach.

1. Introduction

On the path to climate-neutral aviation more efficient and therefore lighter primary fuselage structures are a key factor to improve fuel consumption. Thermoplastic carbon fiber reinforced plastics offer hereby additional weight and cost saving potentials e.g. due to their weldability. One promising manufacturing process is Automated Fiber Placement as it is an additive and fully automated manufacturing process.

However, process parameters have to be kept in tight tolerances especially if direct consolidation is aimed for. This is only possible if besides fast reacting closed-loop controls planned disturbances such as ply steps and velocity changes are considered. In this paper a concept is introduced that uses a heat transfer simulation to calculate the influence of such disturbances and incorporate it in a model-based control for laser-assisted AFP.

Finite element modelling has been proven as adequate for the AFP process e.g. by Mauerer and Mitschang who build a simulation to define a optimal process window and Stokes-Griffin and Compston who added an optical model to a two-dimension finite element model [3,4].

A linear quadratic regulator is described by Hajiloo et al for a foot heater system [1]. Lichtenwalner et al. developed an artificial network to control a laser heated AFP system. However, with the used slow process speeds a steady state inverse model was sufficient for their feed forward control [2]. A lack of a model-based control for the modern, laser-assisted AFP manufacturing process can be identified in literature.

The paper will first introduce the heat transfer modeling approach for AFP before the MPC design is described. A validation demonstrator is subsequently used to show significant improvement of temperature control as one of the driving parameters for the process.

2. Modelling approach and MPC design

Disregarding the tape with and defining a system border only around the relevant consolidation area assists the design of a computational lean finite element model. Both, tape and laminate are segmented in different areas depending on the boundary conditions: tape run in, laser irradiation area, consolidation area and tape run out (refer to Fig. 1). An area before the nip point is defined to decrease element size due to significant heat conduction in this region.

Interfacing elements such as the mold and consolidation roller are modelled as heat fluxes with constant temperatures. An ambient temperature of 22 °C and a combined heat flux for convection are applied to all edges in contact with air. Infinity areas are added to dampen the results for higher layup velocities, with ambient temperature boundaries on the edges. The laser irradiation is directly imposed on the tape and laminate surface. Losses

* Corresponding author.
E-mail address: lars.brandt@dlr.de (L. Brandt).

https://doi.org/10.1016/j.mfglet.2024.03.021
2213-8463/

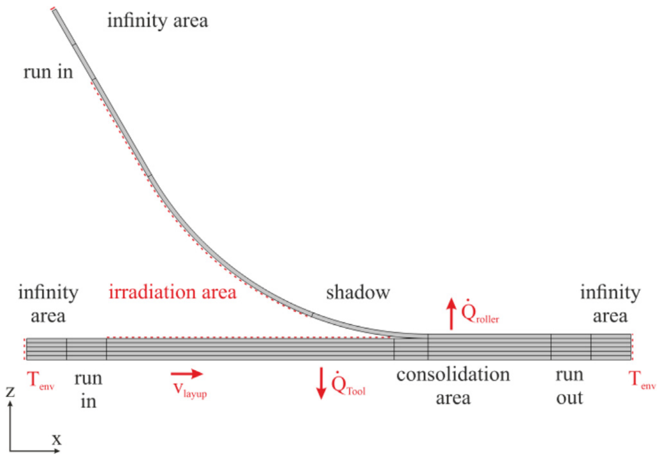

Fig. 1. Modelling Approach FEM.

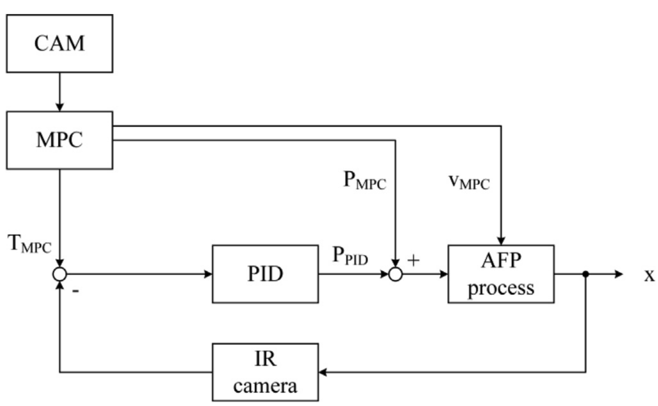

Fig. 2. MPC layout.

e.g. due to reflection are tuned parameters and modelled as factors f_{tape} and $f_{laminate}$. Movement of the layup process is modelled as heat transportation through the material, whereas the anisotropic nature of CFRP is replicated using different heat conduction coefficients for in fiber and perpendicular direction. All key parameters can be found in Appendix A.

The control architecture in which the model is included is depicted in Fig. 2. A computer aided manufacturing software defines the planned disturbances such as layer steps and velocity changes due to geometric features. Laser power and expected temperature are calculated offline using the MPC. These two inputs are used by the PID temperature control during layup by comparing the set point temperature with the actual temperature measured by an infrared camera.

A sample time of 0.05 s and a control horizon of 13 samples has proven to be optimal for the MPC. Laser power and layup velocity are optimized by minimizing a cost function, while constraints are complied with. The constraints define the degradation temperature, that tape and laminate have to be above T_m before the consolidation roller and below after it. These limits are material dependent (here T_m 305 °C, T_{np} 350 °C and T_{deg} 405 °C). The cost function J is defined as:

$$J = \left|T_{npset} - T_{np}\right| \cdot \frac{100}{T_m} + \left|v_{max} - v \cdot \left|\frac{0.5}{v_m}(z_n - z_{n-1})\right|\right| \quad (1)$$

with T_{npset} as set temperature, T_{np} as modelled temperature, v_{max} as upper velocity boundary, v_m as mean velocity and v as current velocity. The vector z is the currently optimized control horizon.

3. Experimental setup

Validation of the designed MPC is performed using a test layup that implements a sudden increase in thickness from two to five layers and a defined drop in velocity from 125 mm/s to 75 mm/s. The trials are conducted using an MTLH layup head manufactured by AFPT GmbH mounted on a KUKA KR120 ultra 2700 robot. It places 3 × 1/2″ tapes in parallel, heated with an infrared laser

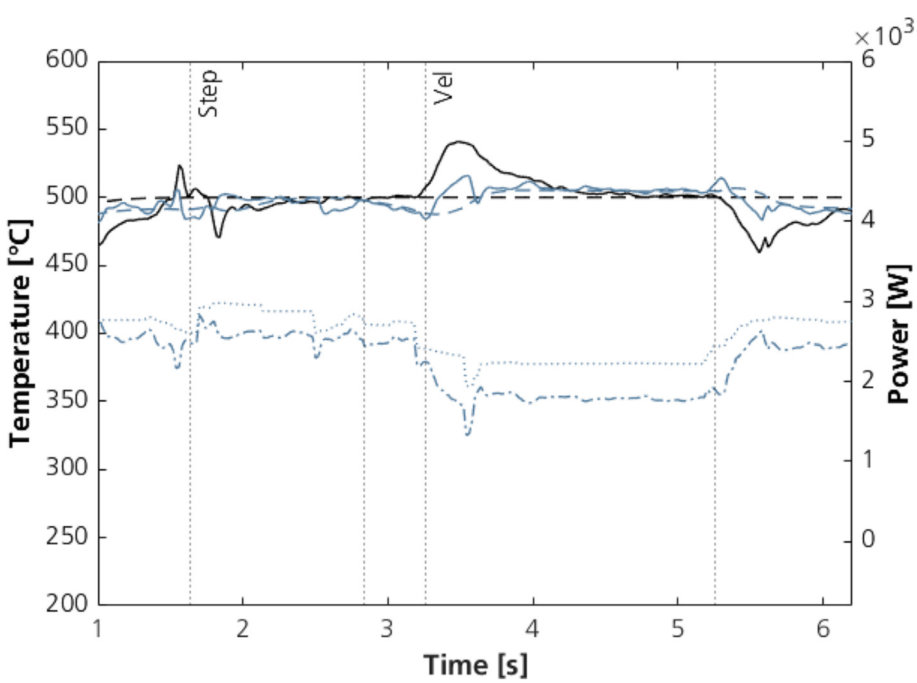

Fig. 3. PID (black), MPC (blue), solid (actual temperature), dashed (set temperature), dots (predicted power), dot-dashed (actual power). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Results MPC control system compared to PID.

	Unit	PID	MPC
Mean ISE		2.4E6	5.4E5
T_{min}	[°C]	455	464
T_{max}	[°C]	548	519
Control Effort	[W]	467	297

system. A standard aluminum mold coated with polyimide film for adhesion is used. The material used for the validation is a CF/LMPAEK TC1225 supplied by Toray. A total of eight measurements for the standard and MPC control system are conducted.

4. Results & discussion

Fig. 3 shows the validation results, where solid lines are temperatures and dashed lines show set point temperatures. The predicted power levels of the MPC are dotted and the actual power used is shown as dot dashed line. All temperature measurements are conducted with a non-calibrated infrared camera which results in an overestimation of the real temperature by approximately 150 °C. The laminate thickness and velocity change are indicated as vertical lines.

A significant reduction of temperature deviation can be seen for both thickness and velocity changes for the MPC compared to the standard PID control. The values in Table 1 show that the overall maximum is decreased by 29 K and the minimum value by 9 K. The MPC power prediction shows that it is systematically to high, however the adjustment to the velocity change is relatively accurate. Compared to the PID control the mean integral squared error (ISE) is reduced by one order of magnitude while the control effort is lower.

A computation time of approximately 5 s per sample results in significant optimization cycle for each track and a reduction is desirable.

5. Conclusion & outlook

Improvement of the control systems for thermoplastic AFP are one main thrust to improve material performance for in-situ consolidation. Complex laminates include predictable disturbances such as thickness and machine induced velocity changes. It is shown that the MPC approach can manage these disturbances. Future work will have to focus on the increase of computational efficiency and a seamless integration of the control in to AFP machine setups.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This project has received funding from the Clean Aviation Joint Undertaking (JU) under grant agreement No CS2-LPA-GAM-2020–2023-01.

Appendix A

Boundary Conditions Model.

Boundary Condition	Unit	Value
T_{env}	°C	22
T_{roller}	°C	120
T_{tool}	°C	22
$h_{convection}$	W/(m^2*K)	15
h_{tool}	W/(m^2*K)	250
h_{roller}	W/(m^2*K)	325
$\eta_{heatsource}$	1	0.7
$f_{tape,\ FEM}$	1	0.55
$f_{laminate,\ FEM}$	1	0.45

References

[1] Hajiloo A, Xie W, Hoa SV, Khan S. Thermal control design for an automated fiber placement machine. *Sci Eng Compos Mater*. 2014;21(3). Jan. 2014.
[2] Lichtenwalner PF. Neural network-based control for the fiber placement composite manufacturing process. J Mater Eng Perform 1993;2(5):687–91. Oct. 1993.
[3] Maurer D, Mitschang P. Laser-powered tape placement process – simulation and optimization. Adv Manuf Polym Compos Sci 2015;1(3):129–37. Jul. 2015.
[4] Stokes-Griffin CM, Compston P. A combined optical-thermal model for near-infrared laser heating of thermoplastic composites in an automated tape placement process. Compos A Appl Sci Manuf 2015;75:104–15. Aug. 2015.