DEVELOPING CONTROL SYSTEMS FOR THE RADIAL OVER-BRAIDING PROCESS

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Abstract

The polylemma of production describes the delicate balancing act between the dilemma of planning versus value orientation and the dilemma of individual versus mass production. To address to the polylemma of production, the German Research Foundation (DFG) has initiated the Cluster of Excellence “Integrative Production Technology for High-Wage Countries”. To increase potential value orientation, a part of this initiative is focused on developing self-optimization for production systems.

At the Institute for Technical Textiles Aachen (ITA), research is currently being conducted to develop Model-Based Self-Optimization (MBSO) for the radial braiding process used in the production of carbon composites. Self-optimizing systems are those which can independently adjust their own objectives and behavior, as characterized by three actions: (1) analyze the current situation, (2) determine objectives, and (3) adapt system behavior.

This paper describes the first step to develop a MBSO system for radial over-braiding processes: designing a feedback loop to control the braiding angle. An approach for the mathematical description of this system will be presented. Using that description a simulation for the process will be implemented. The control loop will be included in the simulation for reasons relating to the determination of controller parameters and stability testing. This paper closes with an overview of current scientific work being carried out in this project.

1. Introduction

The manufacturing industry is facing a large number of challenges on different levels of production. Manufacturing companies are required to adapt their production to new boundary conditions faster at many different levels, such as management, changing customer demands, dynamic environments and quality problems. This leads to changes in supply and turbulence in the value chain. To overcome this issue, it is critical that enough is known about the materials, resources and processes to predict the system behavior and optimize the production process (cybernetic model). On the other hand, adaptability and viability need to be present in order to accommodate unpredictable and volatile boundary conditions (deterministic model). [1]

The aim of self-optimizing processes as defined by the Cluster of Excellence “Integrative Production Technology for High-Wage Countires” is to combine the advantages of the cybernetic and deterministic models. This should be achieved by changing the internal state or structure of the system endogenously according to changes of the external conditions [2]. An operational self-optimization system has already been implemented on the weaving machine [3]. Now, the long-term objective at ITA is to implement self-optimization on a radial braiding process for carbon composite production.

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Radial braiding is an advanced method for the automated production of near net shape textile reinforced structures, known as preforms. In the radial braiding process at least two yarn systems cross alternately over each other to produce a textile structure. In the next step the braided preforms will be impregnated with a copolymer resin. The braiding process is used to manufacture composite structures in sports, medicine, and the automotive and aerospace industries (e.g. the bumper cross-beam of the BMW M6 [4]).

The most important quality criterion of a braided composite part is the fiber orientation, also known as the braiding angle. The braiding angle correlates directly to the strength of the braided composite. Therefore, the braiding angle is one of the most important parameters to consider in the self-optimizing radial braiding process.

Developing a feedback control loop is one of the steps towards self-optimization defined by the Cluster of Excellence. The implementation of a feedback control loop will allow extending the process to MBSO. This article gives a detailed description of the dynamic behavior of the braiding process as well as its demonstration in a simulated feedback control loop.

2. Model-Based Self-Optimization in Manufacturing Systems

At the machine level MBSO can be understood as an extension of an implemented control system. The extension allows the system to independently adjust its own objectives and behavior, characterized by three actions: (1) analyze the current situation, (2) determine objectives, and (3) adapt system behavior. While the typical feedback control loop controls the system by externally predetermined parameters or adapts them to observed changes of the system (adaptive system), "*self-optimization puts the focus onto the dynamization of the target system. […] a self-optimizing system is able to continuously determine the individual sub-targets based on internal decisions and to dynamically adapt the control path"* (Fig. 1). [5]

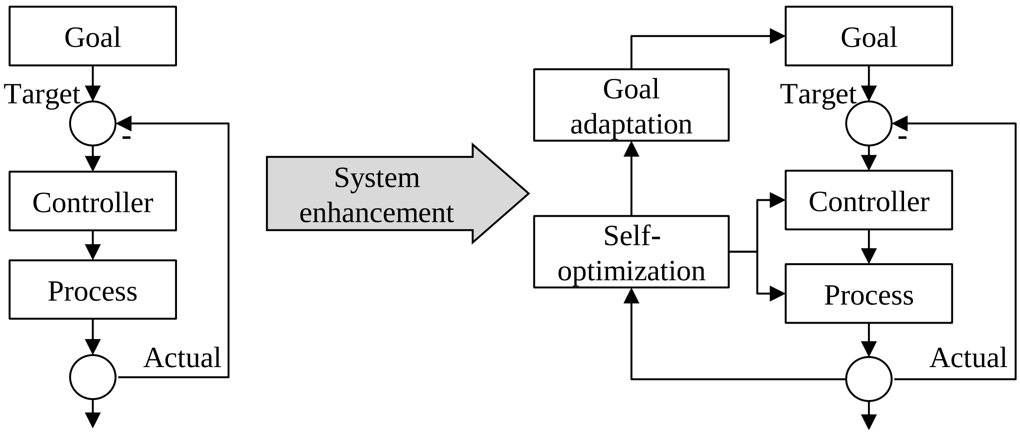

Figure 1. From traditional control to self-optimization [1]

Brecher [5] differentiates between traditional control loop, adaptive control loop and self-optimizing systems. The behavior of a traditional control loop is predefined by external controller parameters. In the adaptive controller loop controller parameters adjust themselves to the target. A self-optimizing system defines its own targets depending on the external goal and changes controller behavior to achieve autonomously defined targets (Fig. 1). It also can be said that the deterministic model is inserted into the cybernetic structure of the system. Therefore, the deterministic model is the basis for the alteration of control structures and target systems. [5]

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At the Institute of Technical Textiles Aachen (ITA) of RWTH Aachen University MBSO is now being implemented step by step on the radial over-braiding process. The first step is the design and implementation of a feedback control loop. The next step will be the extension of the system to achieve MBSO.

3. Radial Braiding

The over-braiding or radial braiding process is shown in figure 2. Here, bobbins are moving on sinusoidal paths (clockwise and counterclockwise) so that the fibers intersect. The fibers, brought together in the middle of the machine by the braiding ring and form the braid at a point known as braiding point (see Fig. 2).

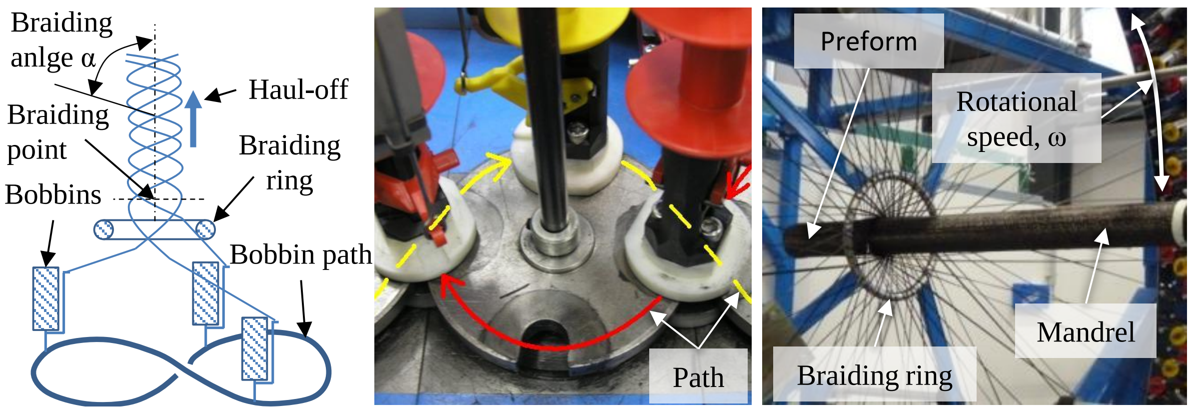

Figure 2. Concept of radial braiding (left), Bobbin path (middle), braiding machine (right)

Nowadays the over-braiding process is used to manufacture net-shape reinforcement (*here: preforms*) for composites such as carbon reinforced plastics for the automobile, aerospace and sports industries. Braiding allows the commercial mass production of fiber reinforced plastic components due to the capacity for automation of the over-braiding processes.

One of the most important quality criterions is the braiding angle, α. The braiding angle determines the resistance to external load of the composite and is defined by the fiber orientation and the haul-off direction (Fig. 2). The braiding angle is the control parameter of the following feedback control system for the braiding process.

4. Feedback Control Loop for Radial Braiding Process

To approach the development of self-optimization, the research in this paper will focus on the creation of a feedback control system for the braiding process. The braiding angle is set by the haul-off speed of the robot and the rotational speed, ω, of the bobbins moving around the mandrel (Fig. 2). The rotational speed of bobbins is linearly dependent on the haul-off speed with regard to the braiding angle. Therefore, the rotational speed of bobbins will be set constant. Only the haul-off speed will be used to control the braiding angle.

For the creation of a control system, it is important to understand the behavior of the system. The steps to create a mathematical model for the over-braiding process and to design a feedback controller will be discussed in more detail below.

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4.1. Differential Equation

To approach the creation of MBSO the current work is focused on understanding the dynamic behavior of the braiding process and the creation of a system to control the braiding angle. In the literature, [6], the dependency of the braiding angle and braiding parameters is described in the following equation:

$$\tan\alpha = \frac{\omega r}{v} \tag{1}$$

ω: rotational speed, v: haul-off speed, r : radius of the mandrel.

Equation 1 represents the static case of the braiding process. To find an equation for the dynamic behavior, the understanding of the forming process of the braid at the braiding point is essential. Nishimoto described the braiding angle as function of time by a step change of the haul-off speed. Unfortunately, the description is insufficient to develop a feedback control [7].

To better understand the braiding process it makes sense to simplify the process. The original system has a high number of fibers moving around the mandrel on sinusoidal paths (Fig. 2), while in a simplified system the motion of only one fiber will be considered. Here the system is considered relative to the bobbin, so the fiber is stationary while the mandrel is rotating at the rational speed, ω, and is hauled-off by v in same direction as before. In this simplification the fiber is stretched between the braiding ring and the braiding point P, which also moves back and forward depending on different parameters such as braiding angle. (Fig. 3) Once the threads touch the mandrel, they do not actually stay fixed to it but are still able to slide along the mandrel until they find a stable or static position. As a simplification, it is assumed that the fibers are fixed to the mandrel as soon as they touch it.

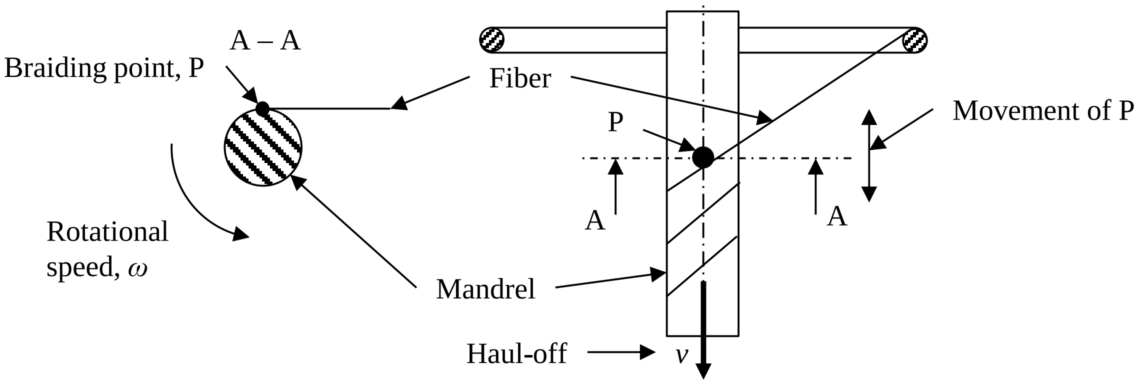

Figure 3. Simplification of the braiding process

Now the simplification of the process is used to describe the dynamic behavior of the braiding process around the braiding point. The main idea is to describe the braiding angle as a geometric function of the distance, h, between the braiding ring and the braiding point (Fig. 3).

The instantaneous motion of point p to point p', represented by the dot-dash line dp, in the small period dt can be considered as a movement of the fiber on a flat plane by unrolling the mandrel surface. This point, p, moves due to the infinitesimal haul-off path vdt and rotational movement rωdt with the fiber. The point P represents the first touching point between the fiber and the mandrel. The point P' represents the movement of the braiding point along the haul-off direction, a distance which is defined by the infinitesimal dh. (Fig. 4)

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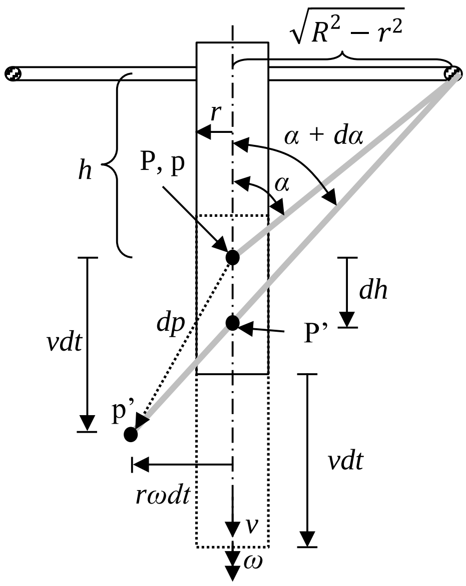

Figure 4. Geometric analysis of the braiding process around the braiding point

The braiding angle is defined geometrically in figure 4 by the tangent:

$$\tan\alpha = \frac{\sqrt{R^2 - r^2}}{h + dh} = \frac{\sqrt{R^2 - r^2}}{h}. \tag{2}$$

It can also be shown that tan α depends on the infinitesimal movement of the aforementioned points by

$$\frac{r\omega dt}{vdt - dh} = \frac{\sqrt{R^2 - r^2}}{h + dh} = \tan\alpha. \tag{3}$$

After some rearrangement the equation (Eq. 4) results in

$$\frac{dh}{dt} = v - \frac{r}{\sqrt{R^2 - r^2}} h\omega \tag{4}$$

or finally with *v* depending on time:

$$\dot{h} + \frac{r}{\sqrt{R^2 - r^2}} \omega h = v(t) \tag{5}$$

This linear differential equation (Eq. 5) describes the position of the braiding point relative to the braiding machine. In the static case the braiding point is considered stable, combining equations 4 and 5:

$$h = \frac{v\sqrt{R^2 - r^2}}{\omega r} \tag{6}$$

$$tan\alpha = \frac{\sqrt{R^2 - r^2}}{h} = \frac{\omega r}{v} \tag{7}$$

This approach of transformation of the differential equation (Eq. 6) is confirmed by the original equation (Eq. 1) for the static case.

4.2. Feedback Control Loop

The next step toward creating a MBSO system will be the development of a simple controller system using the understanding of the dynamic behavior described above. The differential equation (Eq. 5) displays PT1 behavior. Therefore, a simple PI-controller can be implemented. [8] As the main goal is to extend the controller into a MBSO system, it makes sense to directly implement a PID-controller and set the damping factor to zero.

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The draft of the feedback control loop is shown in figure 5. The input of the control loop will be the target braiding angle, the control value is the haul-off speed of the KUKA-robot which can be set over serial communication by changing the internal global variable "OVERRIDE". To measure the braiding angle in real time an optical computer vision system will be used, as developed by Apodius GmbH, Aachen, Germany and named Apodius Vision System (AVS).

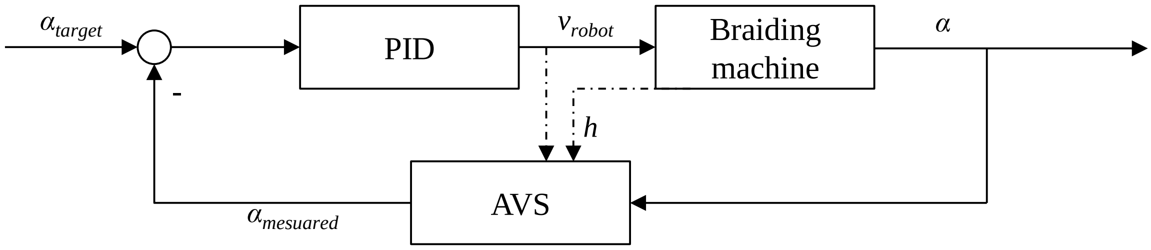

Figure 5. Feedback control loop for the radial over-braiding process

The braiding angle can only be measured after the braiding point. This results in the dead-time dependency in the feedback control system. The dependency on dead-time and implementation of a simple P-controller in a braiding process was already implemented in an earlier project named "AutoBraid" [9]. The camera will be placed at a constant distance l from the braiding ring. In this way it is possible to calculate the dead-time TD. The dead-time TD describes the time passed between the first contact (time t_0) of the fiber at point P (Fig. 4) and the measuring point of the camera. The equation for the time dependency is described in the following equation (Eq. 8):

$$\int_{t_0}^{t_0+T_D(t_0)} v(t)\, dt = l - h(t_0). \tag{8}$$

Unfortunately, the equation (Eq. 8) could not be solved yet. For the sake of simplicity the dead-time behavior will be simulated.

4.3. Simulation

Before the integration of the feedback control system into the real process, it is necessary to prove its stability and dynamic behavior when the dead-time dependency of the process is incorporated into the system. To save the braiding machine from damage a simulation of the feedback control system was used. The simulation was performed in the software package LabVIEW of National Instruments, Austin, Texas, USA.

As the braiding angle input as measured by AVS exhibits noisy behavior, an approximation was made by the measurement of 1000 different points on a braid with the nominal braiding angle $\alpha = 45°$. The measuring frequency of the AVS, limited by the frame rate and software processing time, was set to ten measurements per second (10 Hz). During the simulation an array was created which contains associated positions on the mandrel and the braiding angle as measured at that point (Table 1).

Simulation consisted of the following steps:

1. calculate displacement of the mandrel according to actual speed *v*, new braiding point position *h* and new braiding angle *α*,
2. calculate the current position of the braiding point and save the new angle to the array,
3. when 100 ms have passed, run the camera simulation; calculate the position of the camera depending on the motion of the mandrel, read an interpolated angle at this position from the array, add sensor noise samples,
4. run the PID-controller using measured braiding angle as input and then set new robot speed.

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Position, x [mm]	10,21	10,64	11,06	11,48	11,90
Braiding angle, α [deg]	40,2	40,3	40,5	40,6	40,8

x: Position on the mandrel of the considered point

Table 1. Representative portion of the array built during the simulation

5. Results

The approach to find the differential equation that describes the dynamic behavior of the braiding process was mathematically proved (Eq. 1-8). In a simulation the dead-time behavior was implemented.

The simulation was implemented using LabVIEW. Parameters such as radius of the mandrel, radius of the braiding ring, rotational speed of the bobbins around the mandrel and distance between the braiding machine and the camera have been set as constant. An example of the simulation results is shown in figure 6. The thick gray line represents the braiding angle without delay or noise; the other line represents the measured angle considering the camera frequency of ten measurements per second and including measurement noise. It can be seen that the dead time for smaller braiding angles (higher haul-off speed) is smaller than the dead time for larger angles (lower speed). This means that the dead-time TD is also time dependent due to the changing haul-off speed.

The controller starts working as soon as the first fibers reach the measuring point of the AVS. The PID controller parameters have been tuned manually. The simulation demonstrates the stability of the system.

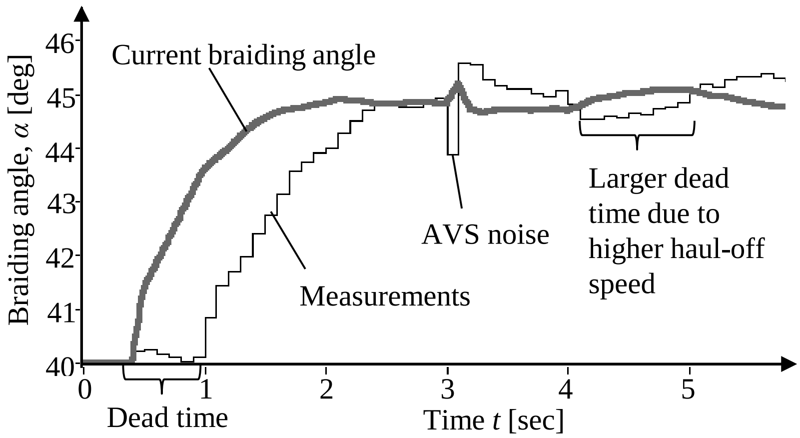

Figure 6. Feedback control loop simulation results for the radial over-braiding process

6. Discussion

The differential equation (Eq. 5) for the braiding process allows estimation of the system response to changing input parameters. For now, the assumed behavior has not been applied to the braiding process. Further practical validation of the feedback control loop is required. Implementation into the radial braiding process will be the next step of this research.

Simulation allows first tests of the theoretical analysis of the braiding process to be performed. The simulation gives the first feedback about the behavior of the control loop before implementation into the real process. The first steps for the implementation of the control loop into the process have been

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completed. The KUKA-robot speed can be adjusted by changing the internal global variable "OVERRIRDE". An interface between controller software and the AVS has been developed.

The PID-controller allows effective target error minimization but is limited to constant cross-section geometry along the mandrel. One possible solution for this issue is to develop a feed forward or even Model Predictive Control (MPC) system for the radial braiding process, which can be incorporated into the MBSO system. A feed forward or a MPC system will allow the controlled production of preforms with non-prismatic geometry to a high standard of quality.

Advancements in automated control and MBSO will significantly increase the abilities of operators to control production and quality, as well as improving overall product quality and process stability. It will also decrease the time required to establish a new product line and the down time between operations by automating significant portions of the quality assurance process.

7. Conclusion

The dynamic behavior of the braiding process has been determined and described by the differential equation and the simulation as described will help to develop a feedback control system and enable future research of MBSO for over-braiding process. There is still some practical work required to implement the designed feedback control system and to test it under real working conditions, taking all disturbances and quality requirements into account.

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