Innovative control system for straightening machines using sensor information from downstream processes

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Abstract. Increasing the sustainability and resource efficiency of forming processes is one of today's major goals. High-strength wire materials are usually available as strip material and are subjected to a downstream forming process such as punch-bending to produce parts for the electronics industry, for example. During the manufacturing process of the semi-finished product, residual stresses and plastic deformations are introduced into the wire by rolling and drawing processes. Straightening machines are used in the production lines to compensate for these. To increase the sustainability of these production lines, the straightening process is an essential step. Before the continuous manufacturing process starts, the straightening process must be set up and the optimal roller positions must be found. Once the process is set up, the roller position settings are usually not changed. Due to missing measurement systems for the straightening quality, it is not possible to dynamically adjust the positions of the straightening rollers to variations in the material properties. This leads to deviations in the dimensional accuracy of the components to be produced and thus to an increase in the rejection rate in the manufacturing processes. To reduce the rejection rate, a novel control system for a continuous feedback control of a straightening process is presented in this paper. This leads to a reduction of the rejection rate and unnecessary preforming operations in wire straightening process. The result is an increasing sustainability and efficiency of these production process.

Introduction

Nowadays, components manufactured in punch-bending machines are an essential part of everyday life. They can be found in various industrial sectors. For example, they are regularly used in the manufacture of terminal blocks in the electrical connectivity industry, where they take on crucial functions [1]. Due to their small size and relatively low unit price, the aspect of sustainability is often neglected, and a high reject rate is accepted, especially when setting up the production processes. This contradicts the concept of sustainability, which is becoming increasingly important in today's world. The aim of this work is to reduce the amount of waste and increase efficiency by applying a novel control approach to adjust straightening machines. The sub-processes straightening and punch-bending are coordinated with each other by exchanging sensor data. In this case, punch bending is an example of a downstream process. An application of the control system for straightening machines in combination with other downstream processes such as progressive processes is also conceivable.

The aim of this paper is to address research questions that deal with the interaction of forming sub-processes. In this case, the focus is specifically on the interactions between the sub-processes of straightening and punch-bending. In a further step, it will be investigated how the straightening process can be adjusted to have a positive effect on the production of punch-bending parts. These findings are intended to enable adjustments in manufacturing processes when fluctuations in material properties occur without having to stop and reset the process.

This paper is structured as follows: First, the state of the art of control approaches for straightening machines is considered. Then the designed system and control structure is presented. On this basis, the dependency between the straightening process and the stamping and bending process is explained. At least, the design of the control algorithm is described and validated on a test rig.

State of the Art

Industrially used straightening machines are usually adjusted manually or by motor and remain in a constant position during the manufacturing process of one coil. This means that fluctuations in the material parameters occurring during the running process have a negative effect on the straightening result [2]. Several approaches have already been pursued in research to determine a suitable roller setting for the straightening process. These approaches can be divided into two groups: Feedforward and feedback control systems.

Feedforward control approaches often work with simulative or empirical datasets. In [3], a method for the numerical determination of the optimal roller position is developed with the aid of an FE simulation. For a specific parameter configuration consisting of material properties, material dimensions, roller arrangement and dimensions, it was shown that the FE analysis can be used to determine suitable positions for the straightening rollers.

In [4], a concept for the automated adjustment of a five-roller straightening machine is presented. Based on a force measurement in the first bending triangle, the material parameters required to determine the roller positions are determined. The appropriate roller positions are known for many different straightening material properties based on a previously performed simulative parameter study. The parameter study is based on the previously described approach from [3].

In [5], a method for online identification of the straightening properties is presented to be able to react to fluctuations in the material properties. This makes it possible to determine changes in the yield strength and the pre-curvature of the steel strip and to readjust the roller position accordingly. The process capability was confirmed by experimental validation tests.

Further examples of simulation models that are used to set the straightening rollers of straightening machines can be found in [6] and [7], among others. However, what all these approaches have in common is that the straightening quality generated behind the straightener is not verified. This does not ensure that the selected roller positions produce the correct straightening result, especially not during the running manufacturing process.

Control approaches for straightening machines are based on this approach. The process quality is monitored, and corrective action is taken by feeding back sensor information. In [8], a control concept for non-rotating straightening machines with an integrated measuring device for determining the residual curvature is presented. The desired value is the lowest possible bending curvature in the processed material at the output of the straightening machine. The position of the wire is identified at three points behind the straightening machine by using optical sensors. With this data a representing value for the bending curvature is determined. In [9], a concept for controlling a straightening machine using a curvature measurement with capacitive sensors is shown. An experimental validation of both concepts is not yet known.

Another concept for online control of a straightening machine for strip material is presented in [2]. For this purpose, the roller positions are adjusted depending on the measured residual curvature of the straightened material after the straightening process so that the strip is as straight as possible. Validation tests have shown that the curvature measurement is the weak point of this approach.

In [10], a concept for controlling a straightening process based on the measurement of the magnetic properties of the material is presented. Considering the Barkhausen effect, a correlation between the magnetic properties of the material and the residual stresses existing in the material is shown. The authors found out that the residual stress distribution is not sufficiently accurate with this type of measurement, which is why the control concept was not implemented. A similar approach was also considered in [11]. Here, the change in the magnetic and electrical properties of flat wire as a function of the bending curvature could be determined by measurement. However, this approach is only applicable under ideal environmental conditions due to the large number of variables, that influence the measured variable.

An evaluation of the state of the art shows that there is a need for a reliable way of evaluating the straightening quality during the continuously running manufacturing process. Furthermore, a control approach needs to be developed that corrects the roller position during the process without pausing it.

System description and control structure

The dynamic adjustment of the straightening rollers during the production process is desirable in order to be able to react to fluctuations in the material properties of the semi-finished product. Focus is placed on the development of a robust and efficient method that does not require time-consuming or resource-intensive preliminary tests and is suitable for industrial use. To develop such an approach, this paper considers the system shown in Figure 1.

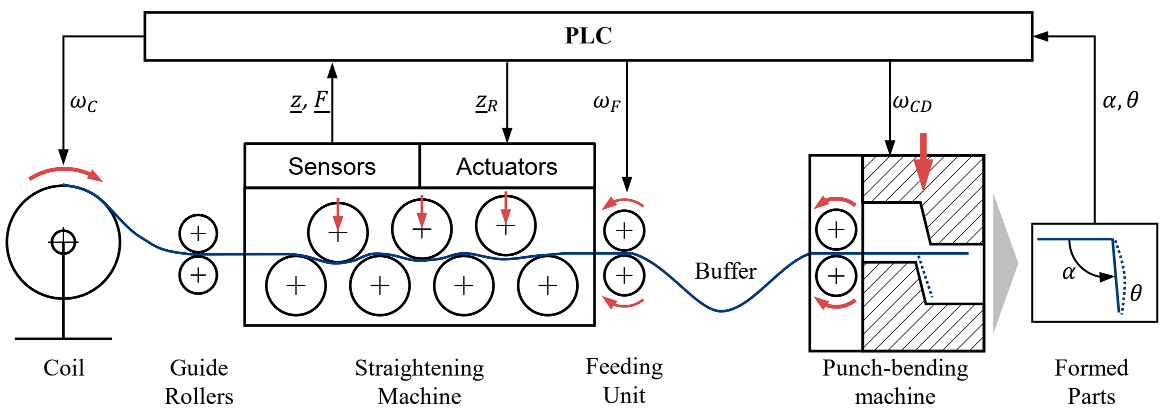

Figure 1: Schematic representation of the entire manufacturing process

The semi-finished product is uncoiled from a coil and fed to the straightening process via guide rollers. This is equipped with sensors to determine the vertical roller positions $\underline{z}$ and the straightening forces $\underline{F}$ on the upper three rollers. The semi-finished product is pulled through the straightening machine by a feeding unit. This is followed by a material buffer to make the transition from the continuous straightening process to the discontinuous punch-bending process. The punch-bending process is used as an example for a downstream process in this paper. There are other possible processes like progressive tools which can be used instead. The punch-bending machine consists of a feeding unit and a punch unit. In this application, an L-shaped component is produced. The bending angle α and the straightness θ of the leg are recorded via a camera. They represent the quality parameters of the manufactured parts and serve as variables to be controlled within a closed-loop control algorithm. The straightness θ describes the magnitude of the curvature of the wire as indicated by the dotted line in Figure 1. However, the focus is on controlling the bending angle α in this paper. For this reason, the straightness θ is not described in more detail. A PLC controls all drives and processes the sensor data. The determining variables for the process speed are the coil speed ω_C upstream of the straightening machine, the feeding speed ω_F of the feeding unit downstream of the straightening machine, and the cam disk speed ω_{CD} of the punch-bending machine. No further control variables are considered in the punch-bending process. The influence of the process speed remains to be investigated. In particular, the tensile force applied to the wire due to feeding can have a significant influence on the straightening process.

The aim of the control approach presented here is the dynamic adjustment of the reference positions $\underline{z}_R$ for the straightening rollers. On the one hand, this should keep the quality of the straightening process reproducible at a high level. On the other hand, it should be possible to react to fluctuations in the material properties with a dynamic adjustment of the straightening rollers in the process. However, as the flat wire is fed directly into the punch bending process, it is not possible to measure the residual curvature directly after the straightening machine. For this reason, the control approach contains three subsystems: the setup assistant, disturbance compensation and feedback control, as shown in Figure 2. The initial positions $\underline{z}_R(t_0)$ of the straightening rollers are determined before the start of the manufacturing process with the aid of a setup assistant. It was presented in [12]. Due to the fluctuations in the material properties, a correction of the initial positions is necessary during the running process. The change in the pre-curvature $\kappa_0(t)$ over the coil radius r_C is interpreted as a deterministic disturbance variable. As part of a disturbance compensation, the trajectory $\tilde{\kappa}_0(t)$ of the pre-curvature is estimated and an adjustment $\Delta\underline{z}_Z$ is calculated using a plant model. A detailed description of disturbance compensation can be found in [13]. The plant model is shown in [14].

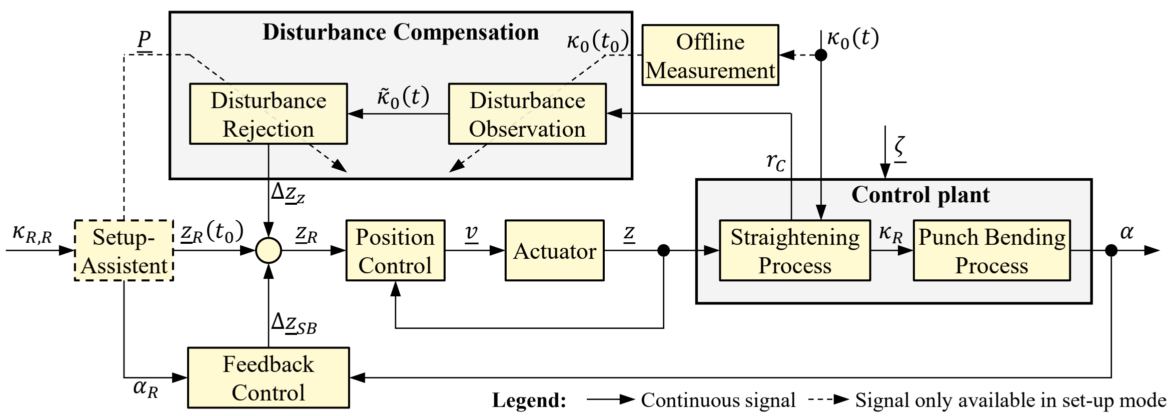

Figure 2: Schematic representation of the overall control structure

In order to compensate for model inaccuracies and stochastic disturbance variables such as width and thickness variations or the material composition, feedback control is used as a third subsystem. For this purpose, the geometric properties of the manufactured component are measured after the bending operation in the punch bending machine. In this paper, the component angle α is considered. In case of deviations from its reference value α_R, a second adjustment $\Delta\underline{z}_{SB}$ for the roller positions is determined. This control approach is based on the two-degree-of-freedom structure (cf. [15]). The reason for using disturbance compensation in parallel with feedback control is the large dead time between the straightening machine and the punch-bending machine. The final reference position $\underline{z}_R$ of the straightening rollers thus results from the addition of the three components:

$$\underline{z}_R(t) = \underline{z}_R(t_0) + \Delta\underline{z}_Z(t) + \Delta\underline{z}_{SB}(t) \quad (1)$$

The reference positions $\underline{z}_R$ are adjusted with the aid of a subordinate position control. The straightening rollers thus act on the incoming wire in the first part of the control plant. After the straightening operation a residual curvature κ_R remains in the wire. In the second part of the control plant, the flat wire is formed to components in the punch bending machine. The dimensional accuracy of the components therefore depends directly on the setting of the straightening machine.

This description of the system under test and of the control structure contains the configuration of all sensor information currently available at the test rig. The focus of this paper is on the presentation of the control algorithm. To influence the residual curvature of the wire when it leaves the straightening machine, it is sufficient to control only the position of the straightening roller in the last bending triangle. Therefore, from now on a straightening machine with only one straightening triangle and one variable straightening roller position z_R is considered.

Analysis of the punch-bending process and controller design

To develop and design a suitable control algorithm, it is first necessary to investigate the dependencies between the straightening machine and the downstream process. A single-stage punch bending machine is considered in this paper and schematically shown in Figure 3 (a). The flat wire is fed into the forming zone via a feeder. There, the downholder holds the flat wire in a fixed position while the bending punch performs the forming operation. At the same time the cutting punch separates the component from the rest of the flat wire. The bending and cutting punches are moved by a cam disk driven by an electric motor. The formed component is characterized by the bending angle α. A camera was installed on the test bench to record this during the process. The setup is shown in Figure 3 (b). The camera with lens is positioned directly in front of the forming zone of the stamping and bending machine. A backlight LED makes it easier for the camera to identify the component. The image is captured at a specific time after the component has been formed. The camera software is used to determine the bending angle α and transfer it to the PLC.

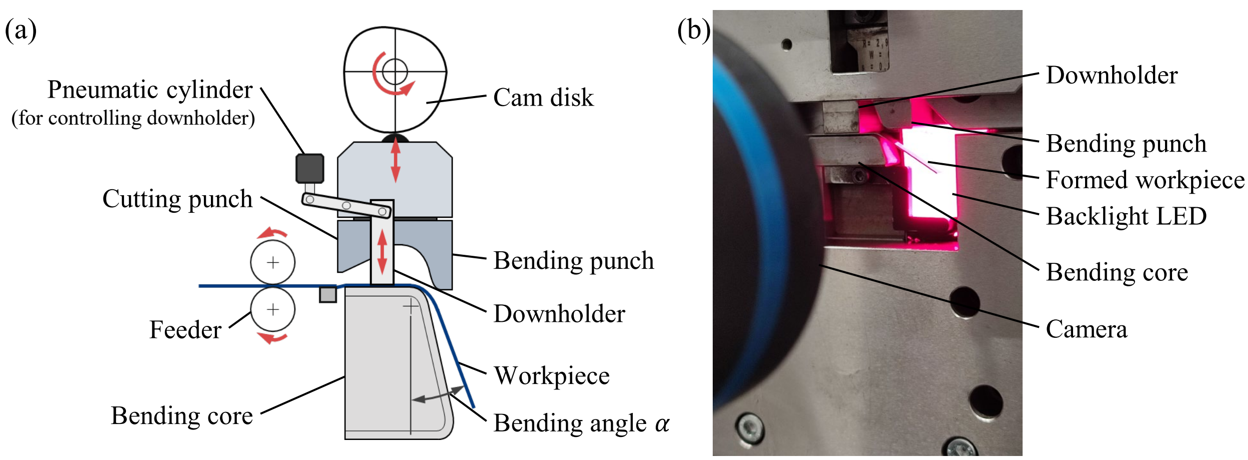

Figure 3: Representation of the Punch Bending process; (a) Schematic representation; (b) Photographic representation of the forming zone

The effect of the straightening process on the bending angle α of the manufactured component is now to be investigated for the design of the control system. For this purpose, samples with different curvatures are produced in the straightening machine and fed into the punch bending machine. The investigations are carried out on flat wire made of high-strength steel (material designation 1.4310) with the dimensions 3.9 mm x 0.4 mm (width x thickness). Samples were produced with a curvature of $B_{Rest} = \pm 25$ mm / 200 mm. The gradations in the range $B_{Rest} < 0$ were selected finer. After evaluating these samples, the area $B_{Rest} > 0$ was divided more coarsely to confirm the trend. The value B_{Rest} is a value to quantify the bending curvature κ and can be calculated using the following correlation:

$$R = \frac{1}{\kappa} = \frac{B_{Rest}}{2} + \frac{L^2}{8 \cdot B_{Rest}} \quad (2)$$

R is the radius of curvature and L is the reference length for the characteristic value B_{Rest}. A reference length of $L = 200$ mm is used in this paper.

Approx. 200 components were manufactured for each curvature. The result of this experimental study is shown in Figure 4. In Plot (a), an example of the component angle for the curvature $B_{Rest} = -0.53$ mm / 200 mm over the number of components produced is shown. 80 percent of all components are within a band of ± 0.1 degrees around the mean value. Except for four outliers, the remaining 20 percent of the components are close to this band. To evaluate the test, the mean value of all manufactured components was saved together with the curvature of the flat wire. After completion of all the tests, all the mean values were plotted over their curvature value. The result is shown in Figure 4 (b). There is a direct correlation between the curvature of the wire and the component angle. The component angle α increases when the curvature B_{Rest} of the wire decreases and the other way round. This correlation can be described by a linear function:

$$\alpha(B_{Rest}) = -0.085 \cdot B_{Rest} + 55.085 \quad (3)$$

The root mean squared error (RMSE) was calculated to determine the accuracy of the linear approximation. This is RMSE $= 0.166$, which indicates a clear correlation.

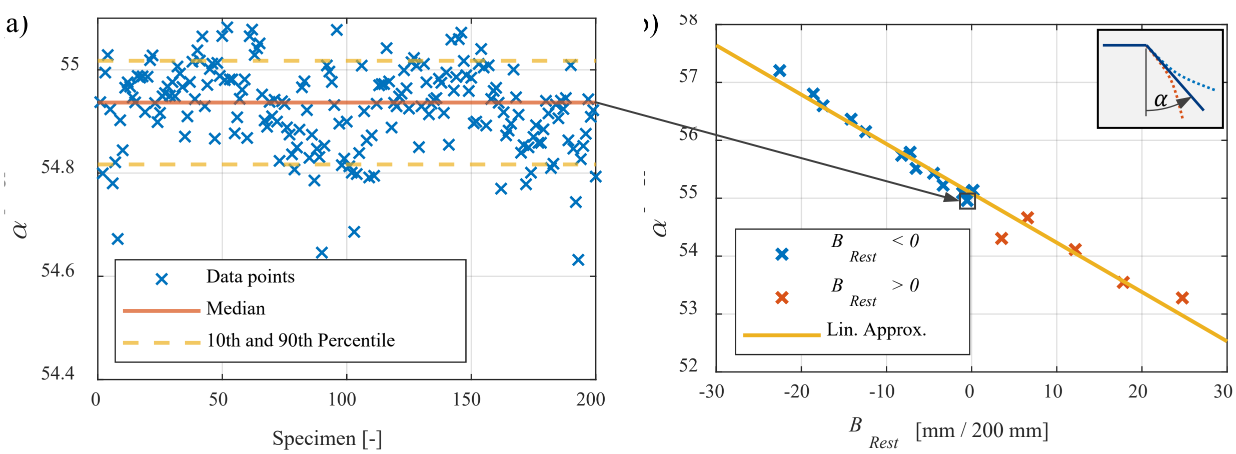

Figure 4: (a) Behavior of the bending angle $\boldsymbol{\alpha}$ *with constant wire curvature* $\boldsymbol{B_{Rest}} = \mathbf{-0.53}$ *mm / 200 mm; (b) Behavior of the bending angle* $\boldsymbol{\alpha}$ *with variable wire curvature* $\boldsymbol{B_{Rest}}$

The control design is described based on the previous investigations. In Figure 5, the control algorithm designed for this purpose is shown schematically. The measurement signal of the component angle is first processed. A moving average filter is used to reduce the influence of outliers on the control variable. Therefore, a filter window size of 10 measured angles is used. After that, the averaged component angle $\overline{\alpha}$ is compared with the reference value α_R and the control difference e is fed to a PI controller. The calculated actuator variable u is limited, as the position of the straightening roller can only be adjusted within certain limits. To prevent the windup effect, an anti-windup element is also used.

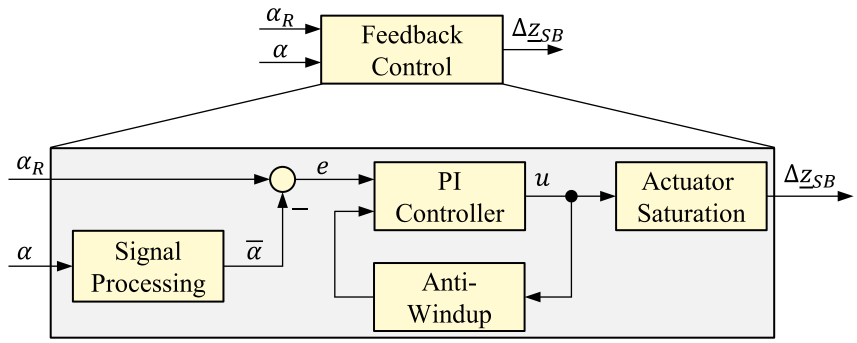

Figure 5: Detailed description of the control algorithm

The values of the PI controller are chosen to $K_P = 0.01$ and $K_I = 0.0025$. The time constant of the anti-windup element is set to twice the value of K_I to $K_W = 0.005$. The actuator variable limit is set depending on the current operating point, which is previously determined by the setup assistant (cf. Figure 1). In the configuration considered here, a range of $-4 < z_R < 0$ is available as the absolute position for the straightening roller. This range is limited by design, among other things.

Validation

After the controller has been designed, proof of its functionality is to be provided as part of the validation process. For this purpose, the test bench described above in Figure 1 is fully set up. The dead time in the current configuration is 34 components due to the distance between the straightening machine and the punch bending machine at the test rig. The distance can be significantly reduced in machines on the market. To verify the function of the control system only one straightening triangle is used. Depending on the straightening strategy and application, the use of a five- or seven-roller straightening machine is suitable. However, the residual curvature in the flat wire after the straightening machine is particularly influenced by the configuration of the last straightening triangle. For this reason, only one straightening triangle will be considered in this paper. The straightening roller position is initially set to the value $z_R(t_0 = 0) = -2$ mm. This results in a component angle of $\alpha_R = 58.5$ degrees. At time $t_1 = 5$ s, a step to $\alpha_R = 59$ degrees is specified. In Figure 6 , the step response and the adjustment Δz_{SB} of the straightening roller at a process speed of 20 components per minute is shown.

Due to the dead time between the straightening machine and the punch bending machine, the reaction of the component angle α to the change in straightening roller position can only be recognized after a certain amount of time. Nevertheless, the control system can follow the step of α_R. Due to the long dead time, the controller parameters were set very low, which means that in this test configuration it takes 80 components for the control error to be reduced. The tolerance band of ± 0.3 degrees around the reference value is already reached after 70 components. As already mentioned, the number of components will be significantly lower due to the shorter distance between the straightening machine and the punch bending machine on machines on the market.

The current work is concerned with optimizing the controller parameters and implementing a Smith predictor for dead time compensation. This is expected to result in a significant improvement in the performance of the control system.

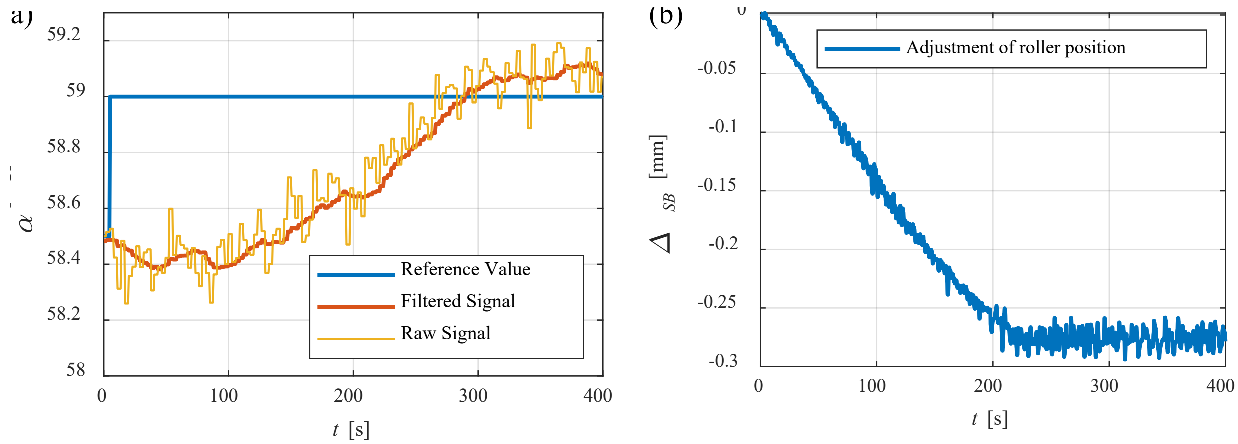

Figure 6: Step response of the bending angle $\boldsymbol{\alpha}$ *(a) and adjustment* $\boldsymbol{\Delta z_{SB}}$ *of the straightening roller position (b) of the designed control system*

Conclusion

In this paper a novel control algorithm is presented, that enables online adjustment for a straightening machine in combination with a downstream process. The straightening quality is evaluated during the running process and the settings of the straightening machine can be adjusted without stopping and resetting the whole manufacturing process. Adjusting the straightening process online enables the possibility of a demand-oriented straightening strategy. Also, the amount of waste caused by re-setting the machine is reduced to its minimum.

This method offers new possibilities for an efficient and resource-saving manufacturing process. It reduces the number of straightening rollers compared to conventional methods and avoids overbending by straightening the semi-finished product as needed. Also, the material's strength properties are preserved by using a minimum number of straightening rollers. This improves the sustainability in two ways: firstly, by allowing for adjustments to material fluctuations and reducing rejection rates. Secondly, the number and complexity of time-consuming set-up processes is reduced to a minimum. This also minimizes the amount of waste that would otherwise be produced when setting up the machines. The combination of these aspects in one manufacturing process promotes responsible and careful resource usage. Currently, there is an estimated potential for material savings of up to 11 % due to shorter setup processes and online adjustments, but further research is needed to validate this control concept.

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