Development, Implementation and Evaluation of a Prototype System for Data-Driven Optimization of a Preforming Process

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Abstract. Modern production of fiber reinforced composites via the preforming process is widely used in the industry. A common way to create dry, semi-finished fiber products is forming or draping a textile into a three-dimensional component geometry. The punch and die process is often used for resin transfer molding (RTM) composite manufacturing. Due to the major influence of the preforming step on the later mechanical performance of the component, a detailed knowledge of the fiber architecture is beneficial.

To enable in-situ monitoring of the specific deformation of a woven fabric, a novel kind of single-use two-dimensional strain sensors has already been developed and characterized. We show that by using industrial communication standards, data from various data sources can be consolidated in an edge computer and used to improve the process. To this end, we developed the hardware and firmware of a device that reads out the printed strain sensors and transfers the data to the edge device via IO-Link. In addition, the edge device collects data from a programmable logic controller and is capable of connecting further IO-Link sensors.

Our demonstrator is intended as a proof of concept for in-situ monitoring, data-driven analysis and improvement of the punch and die process and will be further developed. We propose a machine learning-based edge analytics approach for detecting defects and increasing the preforming quality during the draping process. Forming tests with the double-dome benchmark geometry and the carbon fabric which is suitable for industry have been carried out to validate our prototype system.

Keywords: Composite · Draping · Strain sensing · Edge computing · IO-Link

1 Introduction

In-line quality assessment is a standard for modern automotive series production processes. In the manufacturing of high-performance composite structures, a crucial process step is the preforming of dry semi-finished fiber products. For this draping process, to

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date there are no established sensor systems for quality assurance. However, these are necessary for the production of components in order to guarantee the desired quality in an economical and resilient manufacturing process. The presented method is independent of the geometry of the component. We thus seek to present a universally applicable method for the optimization of the draping process.

1.1 Forming of Woven Fabrics

We present an approach for an enhanced textile forming process that uses previously introduced in-situ shear monitoring sensors to analyze the local fiber architecture [1]. Using highly anisotropic reinforcement materials such as carbon fibers, the quality of a component depends to a large extent on the local variations of the fiber orientation. During the forming process, the fabric is adapted to a three-dimensional geometry by relative rotational or lateral yarn movements. Thus, this adaption process has a major impact on the mechanical performance of the whole structure [2, 3]. To ensure good further processing of the dry preform in a subsequent infusion or resin transfer molding (RTM) step, wrinkling during forming has to be avoided by reducing the local shear angle. If this textile can be prevented from reaching its specific locking angle, wrinkling is unlikely to happen [3].

To document the current fiber architecture of a woven fabric optical methods are common and widely used, but these are not applicable in the closed mold process of stamp forming which is investigated here [4, 5]. The application of flat in-situ sensors on the textile and their use in the draping process is therefore beneficial.

In general, the correlation between the shear angle of a woven fabric and the strain sensors used has been analyzed in [1] with the picture frame test setup, where the sensors are orientated according to the crosshead movement of the frame. With given information about the strain ε of the sensor, the corresponding shear angle θ of the fabric can be calculated by

$$\theta = \frac{\pi}{2} - 2 \cdot \cos^{-1}\left(\frac{1+\varepsilon}{\sqrt{2}}\right). \tag{1}$$

1.2 Sensors for Composite Structures and Manufacturing

The increasing need for lightweight fiber composite structures in the automotive, aerospace and energy industries gives rise to a demand for low-cost, high-quality and efficient manufacturing in this field. Automation and quality monitoring will help to reduce waste and resource consumption (e.g. energy, water and materials).

In addition, there is a clear trend toward sensor integration for structural health monitoring during the whole life cycle. The integration of sensors in carbon fiber-based tanks for high-pressure renewable hydrogen storage allows safe weight-optimized tanks due to the permanent monitoring (pressure, temperature, aging).

Work is reported on dielectric sensors, thermal flux sensors, fiber optic sensors and contactless sensors that use ultrasound and electromagnetic waves to provide in-situ production data [6].

A network of 74 sensors, including 57 ultrasonic sensors, is used in the T-RTM molding of a thermoplastic composite battery box cover demonstrator for the CosiMo project. Dielectric sensors detect the flow, cure and glass transition temperature by measuring the resin electrical resistivity. Electromagnetic methods are used to monitor flow, cure, viscosity, polymerization and other properties of liquid resin. Temperature strain is measured by fiber Bragg gratings integrated in the composite structure during the production process. The requirements for measuring quantity, range, accuracy and rate and for energy consumption as well as the type of interface, such as standardized, proprietary or wireless, depend to a large extent on the application.

To our knowledge, no sensors have been used for monitoring the preforming process to date. In our work, we demonstrate the development of a printed strain sensor prototype for industrial applications using IO-Link communication and an evaluation of the sensing signals using machine learning methods.

1.3 Strain Sensing

The resistance R of a conductor depends on the conductivity ρ, the length l and the cross-section A:

$$R = \rho \frac{l}{A}. \tag{2}$$

The elongation $\Delta l / l_0$ applied to the conductor therefore leads to a change in the resistance R which can be used to measure the strain. In commercial strain gauges the relative change in R is very small because of a typical elongation in the order of 10^{-3}. A Wheatstone bridge circuit is often used to increase the sensitivity [7].

For our application, a novel strain sensing element as well as an evaluation method had to be developed, which will be described in Sect. 2.

1.4 Edge Computing

In industrial automation, processes are usually controlled by programmable logic controllers (PLCs). A PLC controls its outputs based on its inputs using a custom program tailored to the process to be controlled. It is, however, not suitable for collecting large quantities of data and analyzing it using complex algorithms, for example from the field of machine learning. Therefore, these tasks are often executed in cloud environments with large amounts of computing power. However, transferring production data into a cloud environment, where the data and the data security are not under the direct control of the operator of the manufacturing process, is not always desired. Additionally, the availability of the data storage and analysis depends on the availability of both the internet connection of the manufacturing plant and the cloud operator's infrastructure.

It is therefore beneficial to implement the data collection and analysis on-site and close to the process. Using an edge computer, which can collect the data directly from the sensors and PLC used in a manufacturing process, eliminates availability issues and ensures low latencies. A drawback of edge computing, however, is the limited computing power. For complex tasks, it is therefore crucial to find solutions that are suitable for the computing resources available.

2 Experimentation

In this work, we measure local fabric deformation using a bindered carbon fiber weave and piezoresistive strain sensors. The following sections will illustrate the materials used and the setup of our prototype system for the draping process.

2.1 Basic Materials

To create the layout of the piezoresistive strain sensors, a screen-printing process is used with SunTronic PTF Silver (AST6400) conductive ink from SunChemical®. This ready-to-use ink is well suited for applications with high elongation, such as strain sensors. The sensors are printed on a thermoplastic polyurethane substrate, which is highly flexible as well. The strain sensors are applied to a Hexcel® HexForce® G0926 carbon fabric, which is a standard textile in the aerospace industry. It is bindered with 2.5% of an epoxy powder binder per side and, in the draping experiments, one layer of fabric with an areal weight of 375 g/m^2 is used.

2.2 Sensor Characterization

We are using the printed sensor layout shown in Fig. 1 to establish the designated strain measurement during the draping process. The basic sensor element is represented by a printed area of 20 x 4 mm, which is connected by silver ink lines with a width of 1 mm, which are also printed and therefore conductive.

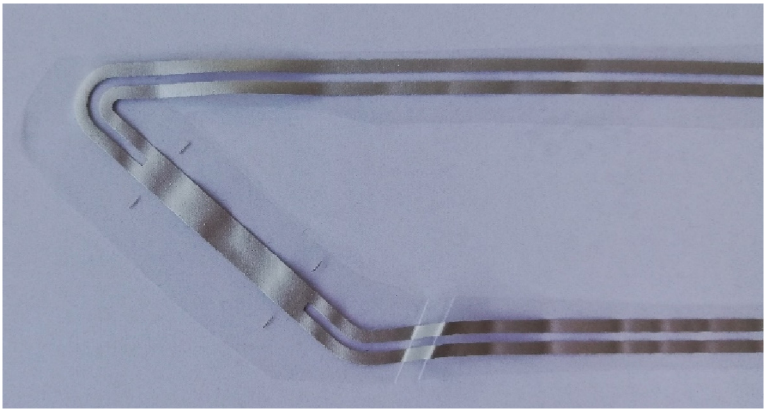

Fig. 1. Screen-printed silver ink strain sensor with marks for ultrasonic welding

Tensile tests are carried out to characterize the resistance over the physical deformation. A 3D-printed test rig is designed and produced for this purpose. With the test rig, tensile tests are carried out between 0 °C and 80 °C in 20 °C increments in the CTS T-40/25 temperature test chamber. The resistance is measured by imprinting 10 mA of current through the feed lines and measuring the voltage across the two sensing lines using a Fluke 175 multimeter. This allows to neglect the resistances in the feed and sensing lines and their variations due to temperature or strain.

As shown in Fig. 2, the change in resistance at 0 °C and at 20 °C is significantly higher compared to the higher temperatures up to 80 °C. The change in resistance in the worst-case scenario at 80 °C is an increase from 0.5 Ω at zero elongation, over 2.4 Ω at 50% elongation, up to 8 Ω at 100% elongation.

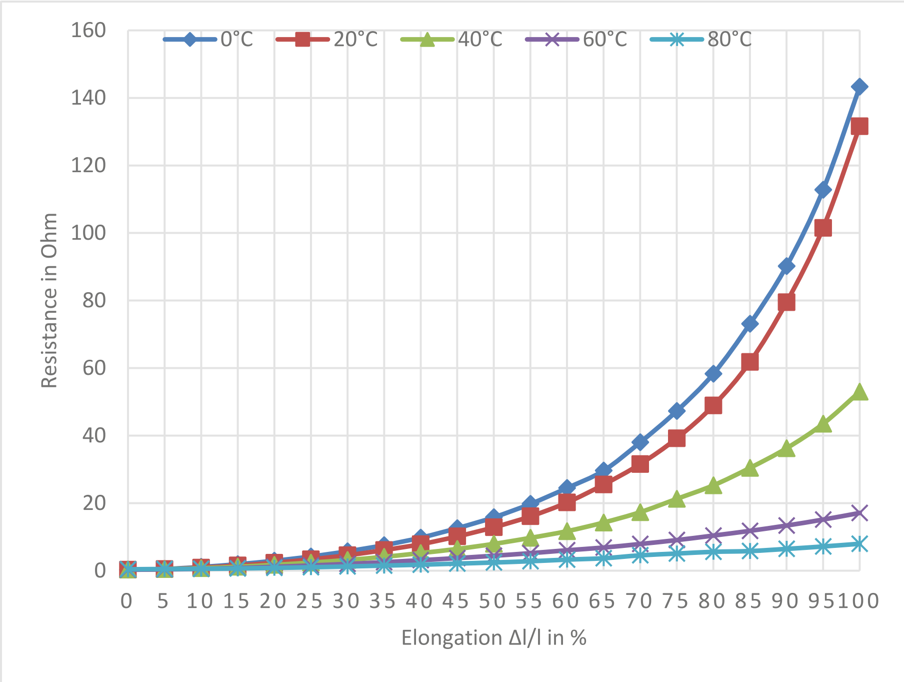

Fig. 2. Resistance over elongation at different temperatures

In [1], several calibration experiments have been carried out, where the printed strain sensors are applied to the Hexcel® carbon fabric in a picture frame test. In this test, the fabric shear is accurately defined and the strain is documented by the sensors. According to the optical evaluation of the shear angles, the strain sensors are well suited for reproducibly measuring the deformation of the fabric.

2.3 Strain Sensor System

A four-wire measurement setup is used to detect the change in resistance. Two wires are used to imprint a constant current into the system. The other two wires have a high input resistance to measure the voltage drop over the sensing element, without being jammed by a change in resistance in the feed line. Multiplexers switch the current and the sensing connections internally to measure up to eight strain sensors in a time-multiplexed manner. The imprinted current is in the range of 1–10 milliamps to keep the voltage over the measuring system below 3.3 V. This low current only generates a small voltage drop across the sensing element. To amplify the voltage over the sensing element, an instrumentation amplifier is used. Its amplification factor can be modified by the resistors that are connected to it. In this work, four different resistors can be connected to the amplifier via dual in-line switches resulting in amplification factors of approximately 1, 10, 100 and 1000.

The constant current source is implemented using an LT3092IST. It is capable of switching between different loads within microseconds, enabling switching frequencies in the range of several kilohertz. Two resistors in parallel set the current to 1 mA. The current is switched between the channels using an SN74LV4051 eight-channel multiplexer. All sensors are connected to a common ground. The other two multiplexers are used to connect the measuring lines to an instrumentation amplifier's input. All multiplexers' address lines are connected in parallel, resulting in synchronized channels. The INA849 is an ultra-low-noise, high-bandwidth instrumentation amplifier, whose amplification can be set using resistors. The output of the amplifier is connected to the analog-to-digital converter (ADC) of the IO-Link board, which also controls the address lines of the multiplexers. Additional DC-DC converters are used to supply all parts with their correct supply voltage. The DC-DC converters are supplied with 24 V from the IO-Link master. The schematic of the constant current source and the multiplexers is shown in Fig. 3.

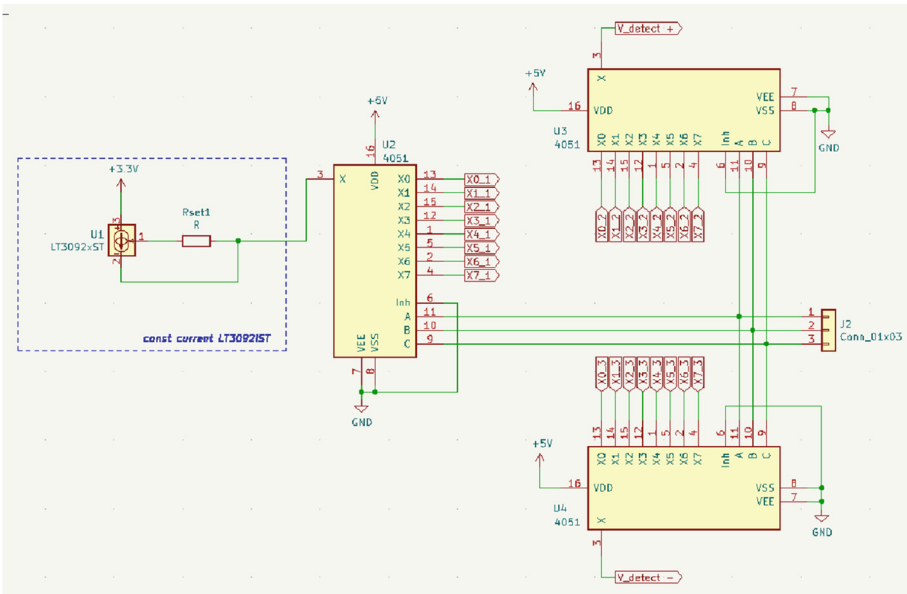

Fig. 3. Schematic including multiplexers and power supply

The IO-Link board runs custom code that switches the multiplexers' channels cyclically and reads the ADC's value in-between. The switching speed depends on the ADC's averaging. With an averaging of 32 consecutive values, the addresses change every 0.66 ms whilst the ADC's values are saved in a ring buffer.

IO-Link is a master driven point-to-point communication protocol. Whenever the IO-Link master requests data, the current data in the ring buffer is transmitted via IO-Link process data.

To allow the sensor box to be recognized by any IO-Link master, we created a custom IO device description (IODD). The IODD specifies how to convert the raw ADC values to human-readable resistance values. In future implementations, it will also be possible to convert the raw ADC values directly into elongation values.

2.4 Integration into Edge Device

To evaluate the data, the sensor values of the PLC and IO-Link boards are collected. The Balluff Condition Monitoring Toolkit (CMTK), which is an edge device containing an IO-Link master, acts as the central device for linking all this measurement data.

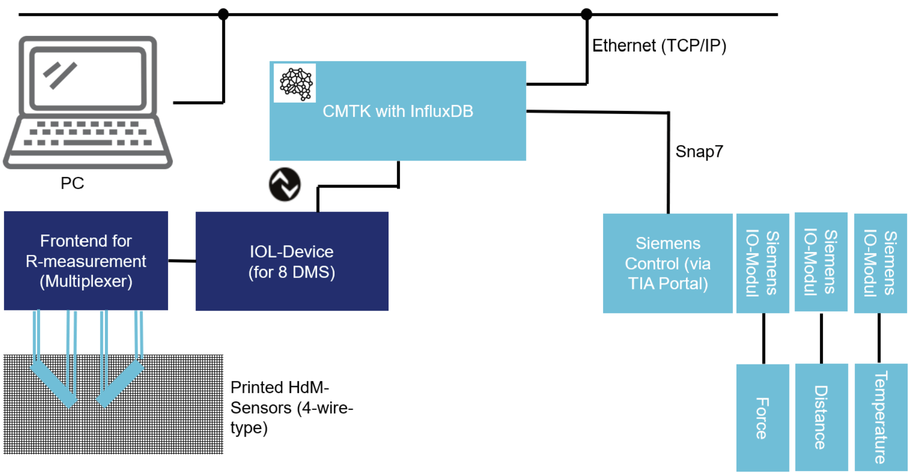

Fig. 4. System architecture with interfaces

Figure 4 shows the complete system architecture with the different communication protocols. These are described below.

The strain sensor system is integrated via the IO-Link ports to the CMTK. This is done automatically via a custom IODD file, which contains the format of the data. The data is processed and sent to the broker in integer values via MQTT. Afterwards, the data is written to an influx database.

A SNAP7 python wrapper interface was used to implement the communication between the CMTK and the Siemens controller. This is an Ethernet communication protocol for native coupling with Siemens S7 PLCs. For this purpose, the data of the various IO modules is stored in a database on the Siemens controller. The data is read out via SNAP7 running inside a Docker container on the CMTK and stored in the influx database.

The data collected from the IO-Link ports and via SNAP7 can then be analyzed, for example with machine learning algorithms running directly on the edge device. Additionally, all of the data stored in the database is made available through a REST API endpoint via a CSV export. Via this CSV export, the data can be further processed on another device.

We implemented a trigger in the control system to prevent the unnecessary storage of data while the prototype system is idle. Only if this is active, will the data from the controller and the MQTT broker be stored in the influx database. This allows for more efficient use of the available memory and more cycles to be stored in the database.

2.5 Draping Process

The printed sensors are applied on the textile material by ultrasonic welding, due to its fast processing and minimal influence on the behavior of the textile during the forming process. The sensors are welded directly on the textile using a VE35 Compactline Solid STE 1200 (from Hermann Ultrasonic) without any additional adhesive and an energy of 20 J per spot weld. The main element of the sensor, which has a length of 20 mm, as well as the ink-printed conduction lines stay unfixed to avoid interference with the measuring signal.

The textile is placed inside the preforming station, which is equipped with an isolated metal double-dome geometry mold for stamp forming (see Fig. 5). The sensors are connected to the sensor box and data is recorded during the entire forming process. To ensure a good draping quality, blank holder plates are placed around the circumference of the textile with a down force of 10 N.

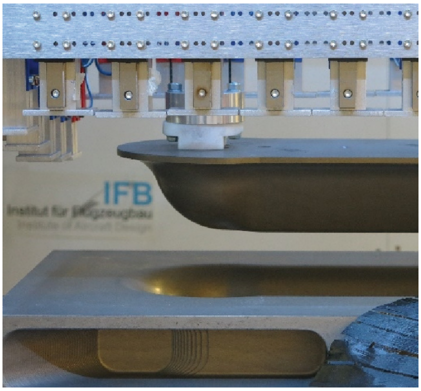

Fig. 5. Stamp mold preforming station

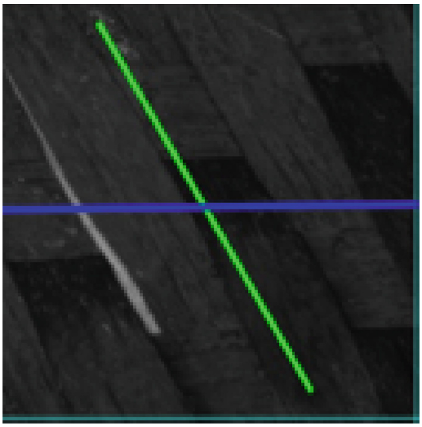

Fig. 6. Analysis of fiber orientation

An optical method for quality assessment similar to [8] is used to validate the shear information based on the strain of the printed sensors. The area where the sensors were placed on the textile is evaluated using grayscale image analysis to obtain information about the local shear angle (see Fig. 6).

3 Results

We show the evaluation regarding elongation values of the strain sensors as a function of the stamp movement during the textile forming process, as shown by way of example in Fig. 7. In total, four printed strain sensors are used on two woven fabrics in an area with a high estimated shear angle. The strain sensors show no elongation during the first half of the forming process. After the stamp moves further into the textile, an almost linear increase in strain is documented. At the final position of the stamp, the maximum elongation of the strain sensors is shown as a numerical value.

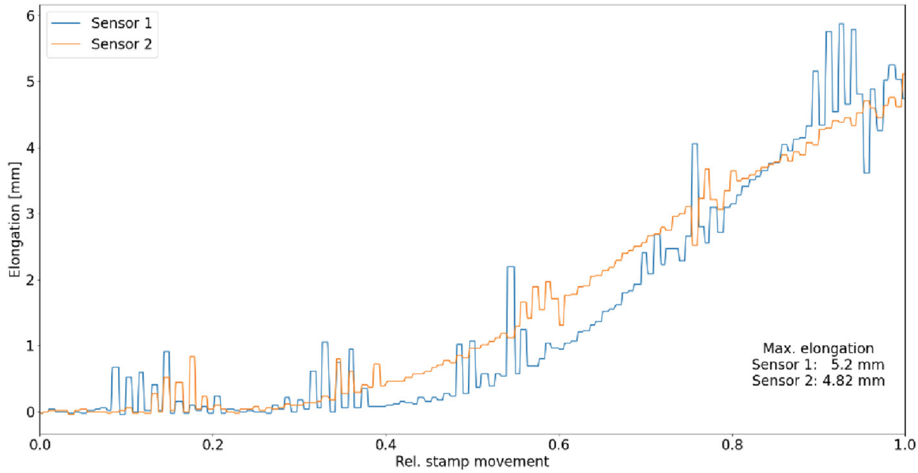

Fig. 7. Sensor elongation over stamp movement

Based on this value and Eq. (1), we estimate the local shear angle of the fabric in Table 1. Additionally, we also display the shear angle which is determined by the optical grayscale method as well as the deviation from the sensor-based data.

In general, good alignment of the shear angle evaluation with both methods can be shown. The small deviation of up to 11% can occur due to the manual positioning of the printed sensors for ultrasonic welding and the tolerances of the optical grayscale analysis. Furthermore, the printed strain sensors show good reproducibility as expected from [1].

Table 1. Shear angle evaluation

ID	Sensor strain ε [%]	Shear angle by sensor θ_s [°]	Shear angle, optical θ_O [°]	Deviation [%]
1	21,4	28,3	30,1	-6
2	20,1	26,3	29,6	-11
3	26,1	36,2	33,7	7
4	24,2	32,9	30,1	9

4 Conclusion

Our work shows that it is feasible to improve the quality of a draping process by consolidating and using data from different sources in an edge device. We developed and implemented the hardware and firmware of an IO-Link-enabled sensor box to read out printed strain sensors. Furthermore, we implemented the communication via IO-Link, MQTT and SNAP7 on a commercially available edge device and successfully integrated the edge device in the draping station. As a first proof of concept, we used the strain sensor data to estimate the shear angles of the woven fabric as an indicator of wrinkling. Forming tests with the double-dome benchmark geometry showed promising results that can be used to improve the process quality.

In the next step, we want to improve the monitoring of the draping process. Instead of relying on the shear angle estimation as an indicator of possible wrinkling, we want to estimate the occurrence of wrinkling and other defects directly from the sensor data using machine learning. Defect detection will be implemented directly on the edge device, enabling the process quality to be improved without additional hardware or cloud computing.

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