IMPROVING THE PRODUCTION QUALITY OF THE ADVANCED AUTOMATED FIBER PLACEMENT PROCESS BY MEANS OF ONLINE PATH CORRECTION

Christian Krombholz* , Marcus Perner* , Matthias Bock* , Dirk Röstermundt*
***German Aerospace Center**
Christian.Krombholz@dlr.de; Marcus.Perner@dlr.de; Matthias.Bock@dlr.de; Dirk.Roestermundt@dlr.de

Keywords: *Automated Fiber Placement Technology, Robotics, Laser Triangulation, Online Path Correction, Quality Assurance System*

Abstract

In order to improve the quality of the Automated Fiber Placement Technology (AFP), the integration of an online quality assurance system is essential. Therefore, the German Aerospace Center uses referencing and monitoring sensor systems to increase accuracy and to optimize tolerances.

This work describes a fiber edge detection sensor which is mounted on a CNC-controlled robot kinematic and determines the relative position of neighbored material courses in order to allow a correction of the actual path of the Tool Center Point (TCP). An online path correction is carried out for the first time. With this knowledge, the control of gaps is enabled.

In addition, the influence of operational vibrations, speed and different motion scenarios on accuracy and repeatability are determined.

1 Introduction

In the aerospace industry, structural components of CFRP (Carbon Fiber Reinforced Plastic) are used with rising trend. Furthermore, the application of composite materials is planned for mass production.

This requires a high throughput of composite materials but based on currently available technologies, a non-appropriate number of plants would be required.

For this, the development of new plant technology for the automated production of large-scale composite components is necessary. However, the conflicting demands for increased quality and quantity should be fulfilled simultaneously.

This demand for a holistic development in the field of composites also adheres to the DLR Institute of Composite Structures and Adaptive Systems which connected the basic research with the industrial application through the opening of the Center for Lightweight Production Technology (ZLP) in Stade and Augsburg in the year 2010.

The development of optimized, reliable, productive and hence also cost-effective production processes are the thematic priorities of the ZLP.

At present, a full scale Automated Fiber Placement (AFP) research facility is being built which will produce composite structures of 20x5.5m^2. The main focus is based on the requirement to increase component quality and quantity.

Fig. 1 shows the Automated Fiber Placement facility of the German Aerospace Center in Stade.

To achieve the quality requirements, a comprehensive quality assurance system (hereinafter called QA system) has been developed and integrated into the manufacturing process and control.

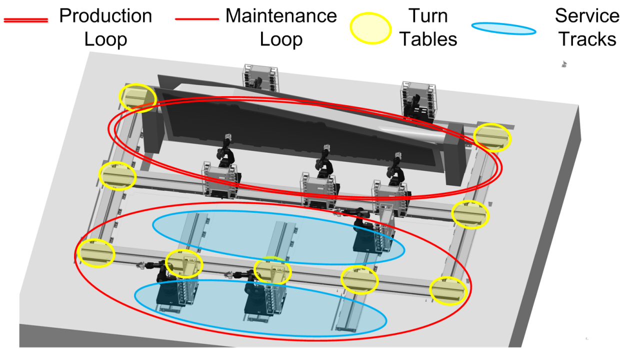

Fig. 1 Automated Fiber Placement facility with 8 coordinated robots laying up on a double-sided molding tool

The QA system is split into three categories: a forerun, a real-time and a follow-up sensor system.

The forerun sensor system detects the edge position of a laid-up neighbor material and starts path corrections to control material overlaps and gaps.

The real-time sensor system is split into a force-torque sensor system on one side. By utilizing this system, the contact pressure of the layup unit can be controlled. A material-optimized production, e.g. of pressure-sensitive materials such as sandwich cores, is given hereby. On the other hand, the use of appropriate sensors and actuators enables a real-time compensation of vibrations to be integrated. [6]

The follow-up sensor system monitors the layup quality through real parameters such as defects, overlaps, gaps, foreign objects, etc. Based on the measurement results, corrections can be initiated within the process. Moreover, the measured edge contour can be used as the base for the forerun edge detection of neighbor material courses.

The existing studies on the forerun sensor system are presented in this paper. The main focus is placed upon feasibility studies of different forerun sensors, the influence of layup speed and movement scenarios on the accuracy and the sensor integration into the AFP plant in Stade.

2 Current technical standard

This section describes the state of the art - related to a quality assurance in the Fiber Placement process, the edge detection and an online path correction of robots.

2.1 Quality assurance in fiber placement process

The adherence to quality and accuracy standards is a primary goal, especially in the aviation industry. The continuous development of new manufacturing technologies enables the compliance with new and more stringent quality and accuracy requirements. Moreover, the demands on a productive manufacturing process increase.

Nowadays a gantry system is implemented into the Fiber Placement process. This lays up the material on a molding tool. The gantry machines have a high stiffness and accuracy - especially repeat accuracy. Thereby, just one accuracy optimization is integrated into the manufacturing process. An offline path-planning system generates all courses with dependence on the ply book. These courses are run once. Simultaneously, an external and highest accurate position measurement system records the current position, compares it with the programmed position and initiates a compensation. An online position-monitoring and correction of the layup unit has not been implemented into the Fiber Placement process yet.

Additionally, the material layup is realized with one layup unit on one molding tool. Thereby, the accuracy of the layup unit can be set as plant accuracy.

A process-related quality monitoring is only partially integrated. After every layup of a laminate layer (ply), a quality control starts. However, this control is very time-consuming and affects the productivity of the plant significantly.

2.2 Quality assurance by means of edge detection

Suitable sensor systems to detect edge positions and to enable a downstream path correction are currently available but technically diverse. The severe demands, particularly concerning the measurement accuracy of the sensor systems, only allow for optical technology.[1] [2] [3] [9]

The measurement of surface characteristics is a major area of application for triangulation-based technologies. Therefore, a laser light section sensor which enables the required measurement accuracy, a high process stability and a compact design is used for fiber edge detection at the AFP plant. [7] provides further explanations of the sensor technology.

The measurement of surface profiles with a laser light section sensor allows several application scenarios: edges, chamfers or grooves.

Nowadays, laser light section sensors are established in the automation branch. The application in sensor-controlled arc and gas welding technologies is one example. Here, the joint geometry is detected to adapt process parameter such as welding speed, voltage, current and the speed of the welding wire. Additionally, the laser light section sensor is also applied as a quality assurance system that detects quality characteristics in a run-down process.[1] [3]

Another field of application is the determination of a board to measure the existence, geometrical contour accuracy and position of individual components.[7]

Furthermore, laser light section sensors are used in body construction to determine gaps between the door frames and the door.[7]

2.3 Path correction

Path inaccuracies in industrial robots are reasoned in the kinematics, the robot mechanics, shifting of various values ober the time and contouring errors of the position control. Therefore, the utilization of sensor-based path corrections is appropriate.[8]

An offline path correction system for industrial robots was presented in [4]. This established the accuracy of the conveyor system and the production tolerances of the work project are most relevant for the complete system's accuracy. Using a standard industrial robot, a laser light section sensor on the robot's hand and an industrial PC, the production process was divided into a measurement and an application run. During the measurement run, data was collected in regard to deviations between the actual and the target path. Reasons for these differences are construction-conditioned positioning limits of the robot and misalignments of parts. In the second step, the robot acts based on the correction results. The independence of the measurement and execution was pointed out as the strategy's benefit. However they suggested an online strategy in case of more pretentious tolerances.

The aim of the work in [5] is the decrease in the difference between the desired and the actual cutting path. These static and dynamic interactions between the robot and the milling process are analyzed. Static deviations by simulation and correction of the milling program are significantly reduced, whereas the inclusion of an additional sensor on the TCP for the compensation of dynamic processes is recommended. These sensors detect the actual path values and pass them to the control and evaluation logic. The following chapter describes the experimental design and methodology presented to qualify the type of sensor for a successful utilization of the fiber placement process. In essence, the requirements for the detection of a carbon fiber edge are pointed out.

3 Experimental investigations

The experiments described in this chapter transfer the determined findings of the preliminary tests on the filament winding plant in Brunswick to the Automated Fiber Placement plant in Stade.

In addition, for the first time an online path correction is performed, which initiates a new path planning during the deposition process with correction values measured by the edge detection sensor.

The detection and the relative position determination of the previously deposited material edge allows an adjustment of the tray accuracies in the manufacturing process and a specific control of gaps.

3.1 Pretests

In previous work, basic research for a reliable and stable edge detection has already been carried out. [7]

In these tests, the major dependencies of the test results of material such as woven or non-woven - uni and multi-directional - were presented.

Furthermore, guidelines could be set for an optimal test environment.

In the foregoing experiments, different laser scanning sensors were also compared with each other. This identified the influence of laser intensity, laser sampling and triangulation angle.

A basic feasibility of the fiber edge detection through the use of a laser section sensor could be demonstrated in these experiments.

Beyond this, in particular the laser intensity in multilayer structures and the pitch angle of the sensor system to the material surface are shown. (see [7])

3.2 Experimental setup

The experiment was carried out at the Automated Fiber Placement research facility of the German Aerospace Center in Stade (see Fig. 1). The research plant includes a circumferential track system. In this track system consisting of linear units and turntables, mobile platforms can be moved.

On each platform, a CNC-controlled 6-axes industrial robot is mounted. Their effectors are a tape-laying or a fiber placement head.

The experiments were performed with the fiber placement head, which already has two fiber edge detectors mounted in the in [7] specified pitch angle.

The material edge was positioned on a test table. The material had an edge length of 850mm and a height of 0.7÷1.0mm.

Only sensor 1 (right) was used for the experiments. Sensor 2 is identical and is used for material edges on the other side.

The fiber edge detectors are mounted in fore-run with a distance of approximately 110mm (sensor offset) from the Tool Center Point (TCP)

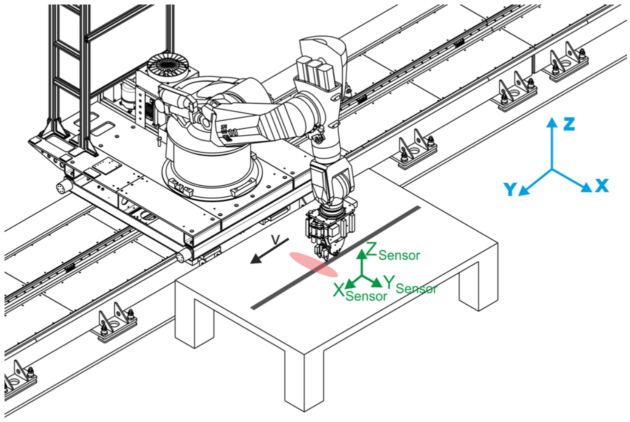

Fig. 2 Test setup with illustrated coordinate systems) - blue: global coordinate system, green: sensor coordinate system

respectively from the pressure roller. This spacing allows a sufficient time and correction path between the measuring signal input and the corrected TCP position.

The following Fig. 3 shows the Fiber Placement demonstrator with both edge detectors (1), the ideal material tape (2) and the laser light (3) at the edge.

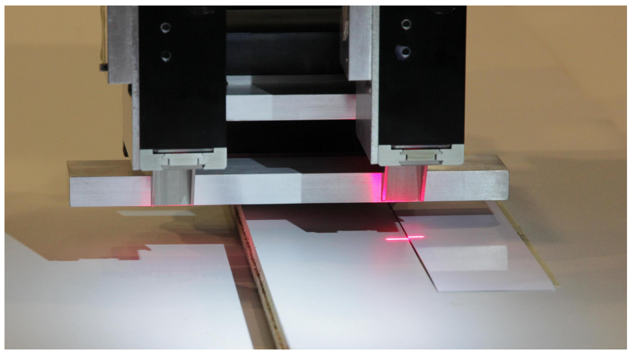

Fig. 3 Photograph of the setup with edge detectors (1), material edge (2) and laser light section (3)

3.2.1 Uncorrected motion

The edge detection was always out of contact between fiber placement head and material edge. This identified the measured vibration of the plant and robot during the experiments.

The operational vibration, which leads forces into the fiber material in a contact way, can be considered independently.

The test table is not coupled with the robot or the end effector, which enables the actual vibrations of platform and robot to be measured.

Due to the six degrees of freedom (DOF) of the robot plus the one DOF of the movement unit, the motion of the platform and robot is not bijective. If the material edge is in the direction of the linear axis (Y-direction), the path can be tracked by a pure robot, a pure linear a or a combination of both motions.

To determine the influences of the operating conditions on the deposition accuracy, the following test scenarios were carried out:

- edge detection for robot motion axes
- edge detection with linear motion axis of the rail system
- edge detection with combined motion of robot axes and linear axis of the rail system

In all cases, the movement along the edge was a point-to-point path.

The programmed feed rate was varied in steps for 6m/min (override = 20%), 12m/min (40%), 18m/min (60%), 24m/min (80%) and 30m/min (100%). The path was parallel to the linear axis.

3.2.2 Corrected motion

In the second test section, the material edge was again detected without contact between the pressure roller and the material.

In this case, the path correction was enabled and managed the path corrections.

The material edge is positioned in such a way that a path correction in Z_{Sensor} and Y_{Sensor}, due to large deviations from the desired path, has to be initiated.

A variation of movement types and feed rates was carried out similarly to the uncorrected measurements. Fig. 4 illustrates the transaction types and the feed rates.

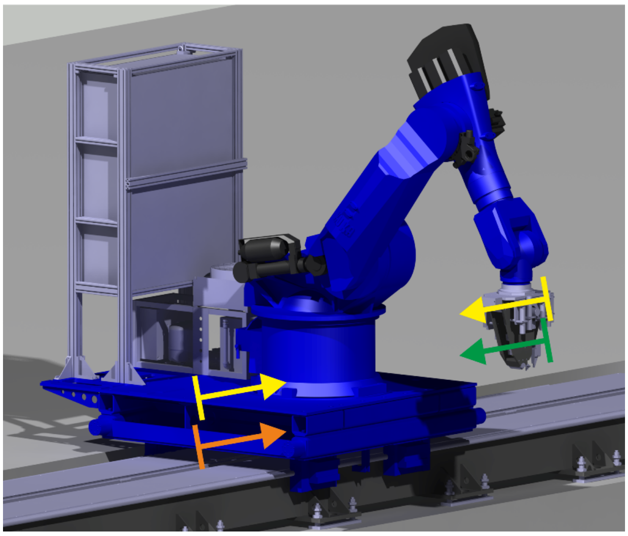

Fig. 4 Representation of the different motion characteristics - orange: moving platform, green: moving via robot axes, yellow: combined moving platform and robot axes

3.3 Sensor integration

This section describes the integration of the sensor system into the plant control unit. The company *ibs Automation GmbH* implemented the contour tracking into the control system of the fiber placement facility - a SIEMENS 840D-SL control.

The edge detection system is mounted on the end effector of the industrial robot kinematics. To enable an online path correction by reference to neighbor material tapes, the sensor is positioned in direction of movement in front of the TCP. The vectorial offset between TCP and origin of the sensor is called "‘sensor offset"’ (Fig. 2) and influences the reaction time and the path length for a path correction.

The CNC-integrated 3D-contour tracking is based on an industrial robot with up to 7 axes, which has an open NC kernel. The data flow is shown in Fig. 5.

By means of triangulation, the sensor measures geometrical data of a surface structure positioned in the field of vision. From this data, the sensor PC calculates the edge position in sensor coordinates. This information is cyclically transmitted to the CNC control within the compile cy-

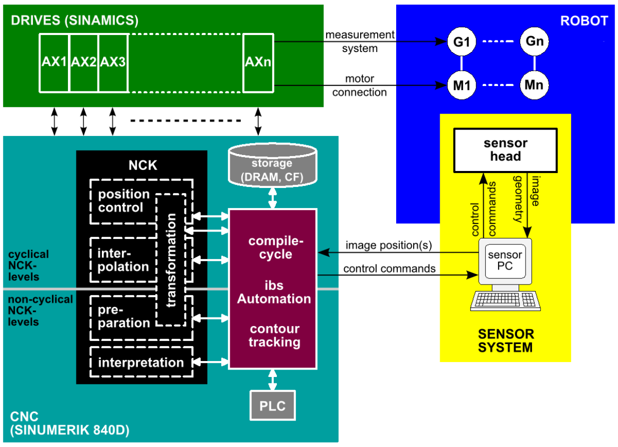

Fig. 5 Data flow of the CNC-integrated contour tracking

cle "‘CNC-integrated contour tracking"’.

Interpretation of the control-based robot position, the information from the edge-detection system and the actual NC-file may initiate an online path correction. For this case, new NC blocks are generated and implemented into the control cyclically.

The compile cycle communicates with all levels - the SINUMERIK 840D-SL, the PLC (Programmable Logic Control) and the storage. The compile cycle is an expansion of the SIEMENS 840D-SL CNC operating system (NCK-OEM application).

4 Data analysis

This section describes the data analyses of the experiments. After the description of the signal processing, the results of the uncorrected and corrected movements are presented.

4.1 Signal processing

Signal processing of measured data is one of the decisive steps in the integration of the online path correction. The most important signals for edge detection are:

- y-position of left and right edge - Y_{Sensor}
- z-position of left and right edge - Z_{Sensor}
- edge indicator as a quality value

The principle nomenclature is schematically illustrated in Fig. 6. For this purpose, the edge indicator is influenced by the intensity of the reflected laser light and the sharpness of the measured edge.

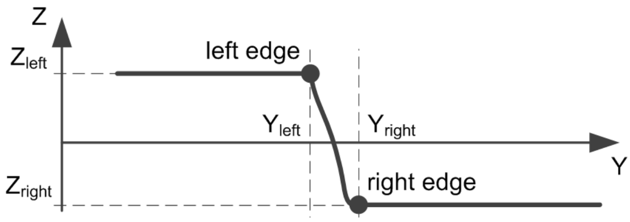

Fig. 6 Scheme of the co-ordinate system of the laser stripe sensor

To perform the signal analysis a Matlab®-based tool is created.

Firstly, the original signal data, shown in Fig. 7, is filtered by the edge indicator defining a threshold value. This indicator determines the quality and reliability of the measured edge.

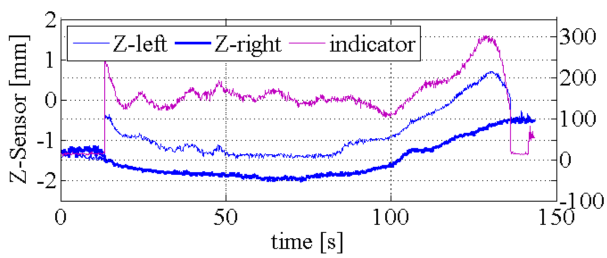

Fig. 7 Original data

In the next step, the offset between the z-position of the left and the right edge is used as a threshold value filter defined by the minimal edge height. Using a defined movement speed and scenario, a representative signal is obtained by calculating the mean signal of the synchronized single data series. Deviations in the start times results in signal movements along the time axis. To synchronize this, the cross correlation function of all data is used to obtain the time offset. Now, the data is shifted along the time axis in regard to the cross correlation maxima.

Finally, the five data series for every motion scenario and speed are averaged, shown in Fig. 8.

Additionally, the standard deviations of every test setup are calculated.

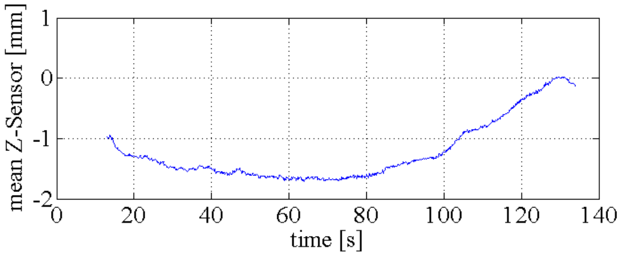

Fig. 8 Mean Z-position

standard deviation [μm]					
motion scenario	**speed [m/min]**				
	6	**12**	**18**	**24**	**30**
linear axis	6.5	6.7	7.8	7.4	13.6
robot axes	5.8	5.0	4.7	4.3	4.2
robot + linear	9.5	11.1	12.8	9.6	10.0

Table 1 Standard deviations in Y_{Sensor}-direction

In the next step, every averaged data series is re-sampled to compare different speeds of one motion scenario. By calculating the correlation coefficient of every speed to the minimal speed of one motion scenario, the considering of similarity is enabled.

4.2 Uncorrected motion

Evaluation of the measured data and demonstration of plant characteristics forms the main content of this section.

Firstly, the measurement accuracy of the sensor system was determined by its repeatability. Fig. 9 shows exemplarily the measurement series with a combined motion of platform and robot axes at a constant speed of 30m/min.

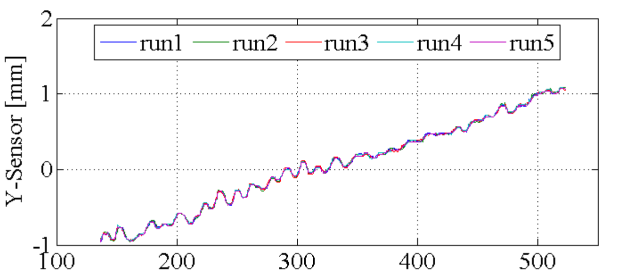

Fig. 9 Measurement series of the Y-position with 30m/min and combined linear and robot motion

[7] already showed that the accuracy of the sensor system is in the lower micrometer range. Fig. 9 also determines that the measured vibrations of the kinematics is based preponderantly on the motion and not on the noise.

The standard deviations of the different motion scenarios and speed are listed in Tab. 1.

The limit of the standard deviations is 13.6μm and results in a good reproducibility and stability of the measurement data.

In a second analysis edge detections at different speeds were compared within one motion scenario. The exemplary results are shown in Fig. 10.

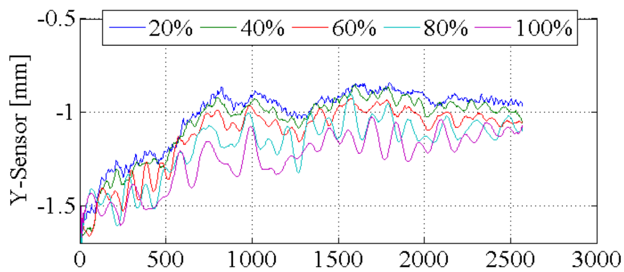

Fig. 10 Linear axis motion with all speeds - 20%=6m/min, 40%=12m/min, 60%=18m/min, 80%=24m/min, 100%=30m/min

Clearly visible is the dependence between speed and vibration amplitude. Increasing speeds results in increasing vibration amplitudes as well. A comparison of the correlation coefficients shows this dependence, too.

The values of the correlation coefficients of every speed by every motion scenario are shown in Tab. 2.

correlation coefficient [%]					
motion scenario	**speed [m/min]**				
	6	**12**	**18**	**24**	**30**
linear axis	100	99.9	99.9	99.7	99.5
robot axes	100	99.9	99.9	99.9	99.9
robot + linear	100	97.8	88.6	75.8	75.3

Table 2 Correlation coefficients

In addition, an offset of the measurement series has been measured. It is found that the edge position shifts into the Y_{Sensor} direction with increasing speed.

For all measurements at different speeds and motion scenarios the reproducibility of the measurement results has been demonstrated.

Particular attention should be paid to compensate the different operating vibrations that could affect a benefit for a future online path correction. This influence has to be proved in further tests.

Moreover, it was shown that varying speeds result in inaccuracies. Without an edge detection and a subsequent online path correction these inaccuracies are not compensable. For a required quality improvement, an online correction is necessary and definitive.

4.3 Corrected motion

This section deals with the online path correction.

The measurement results of the previous section show that the requirements regarding the measurement accuracy of the system are fulfilled. Additionally, the influences of speed and different movement scenarios on the position accuracy of the plant are determined. Especially the displacement of the series at increasing speeds and movements by the linear axis requires an online path correction.

For the first time, an online path correction is carried out.

For this, the edge is detected by varying the motion scenario and speed with a following online path correction.

In the course of the online path correction, new NC-files are generated and transferred to the control unit (section 3.3).

The corrected courses are displayed in the global coordination system and are shown in Fig. 11 and Fig. 12.

The computed standard deviations are in a very good range - both in X-direction and Z-direction (see Fig. 13).

With the exception of one peak, all standard deviation data are below 100μm - in Z-direction even below 50μm. The average standard deviation is 37.7μm in X and 25.0μm in Z-direction.

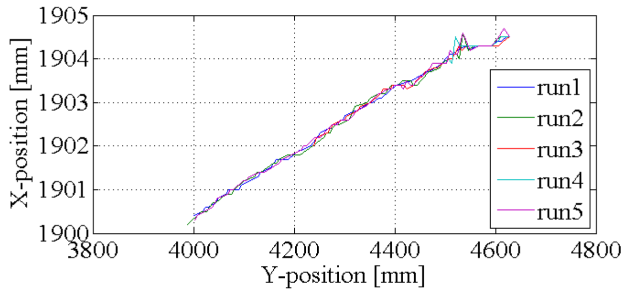

Fig. 11 Corrected path in X-direction

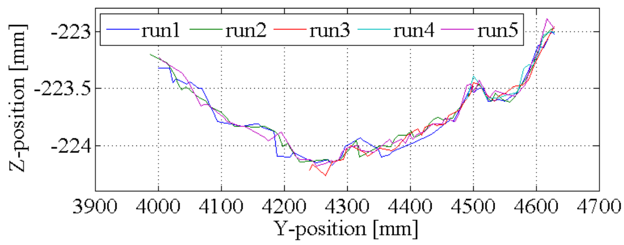

Fig. 12 Corrected path in Z-direction

At all variants an online path correction is feasible.

A comparison of the correct path with those described in the section "‘uncorrected movement"’, is displayed in Fig. 14. For a better optical comparison, the data of the corrected NC-files is presented reverse.

It becomes obvious that the courses of the curves are very similar. Thus it is indicative for a patent online path correction.

Currently, algorithms interpret data by an average over a specific range. The causes of these averaged data, vibrations and temporary inaccuracies do not influence the correction path as much. If the measurement data is above a defined tolerance limit, the speed will be decreased. For the majority of the measurements, the speed was controlled, so that comparisons of the path correction at different speeds were not significant.

In addition, an influence of different motion scenarios on the accuracy is not detectable - only on the speed.

5 Conclusion and outlook

The analysis of uncorrected and corrected motions and the impacts of speed and motion sce-

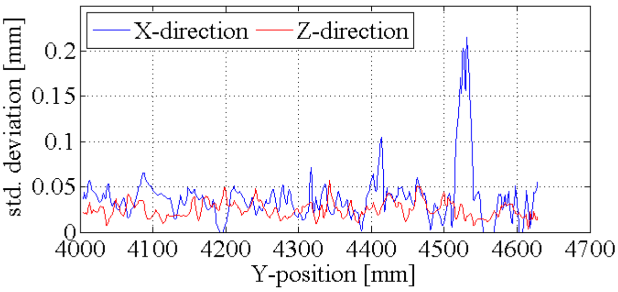

Fig. 13 Standard deviation of measurement series in x and z direction

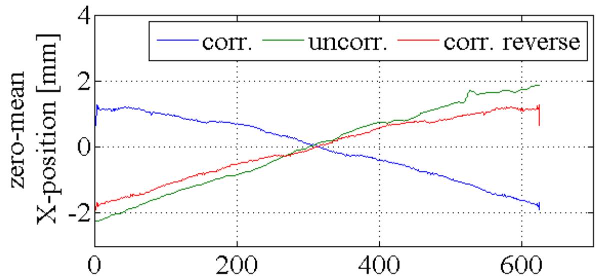

Fig. 14 Comparison of a corrected with an uncorrected edge detection

nario are demonstrated successfully.

The increase of speed determines low influences on the standard deviation. Just by moving the linear axis, the value rises from 6.5 to 13.6μm. But in every case the standard deviation is below 13.6μm and shows a very good repeatability.

Additionally, the increase of speed raises the vibration amplitude. To attenuate the vibration amplitude, several methods will be discussed.

In addition, for the first time an online path correction of a CNC-controlled robot kinematics is performed. The average standard deviations in x and z-direction show a good repeatability as well. A measurement stability has been shown.

Furthermore, the necessity of an online path correction for a high precision material layup is demonstrated.

The operational vibrations, which lead forces into the fiber material in a contact way, are considered independently. Studies at the DLR will create a compensation model that minimizes the vibrations. [6] Parallel to that, the effects of external forces on the fiber material are analyzed. The results will be traced back to a more accurate and faster material layup.

In continuing studies, the influences of speed and operational vibrations on the pre-preg material will be conducted as well.

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5.1 Copyright Statement