Industrial IoT system to support the assembly of large components

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Abstract

Smart and networked sensors are conquering industrial applications in addition to the consumer sector. While the costs for manufacturing and the required installation space are constantly decreasing, the functional performance of these technologies is growing. In the industrial environment, they are used to acquire measurement data, digitize processes, enrich digital twins with information, and reveal cause-and-effect relationships. Companies have recognized the opportunities offered by this digital transformation and smart manufacturing.
The paper starts at this point and explains how IoT technologies and precision measurement tools can be combined to support handling of large components in manufacturing. It describes a developed sensor gateway and its possibilities to optimize the complex joining process of two fuselage sections in final aircraft assembly. A high number of previously complex and time-consuming manual measurement steps will no longer be necessary in the future with the use of this smart and networked sensor technology. We address the developed sensor tools, describe how the data are collected in the process, and we support the assembly via a kinematics model. An evaluation on the developed technology demonstrator underpins the results with realistic measurement data.

1 Introduction

1.1 Motivation

Assembly processes in aircraft construction have a high proportion of manual activities. Particularly when joining large components spatially widely spaced reference points must be monitored. Geometric measurements performed here must be recorded synchronously in time. They must be weighted according to allowed tolerances or current measurement uncertainty and translated into instructions for the acting persons.
An example is joining wings, which are more than 15 m long, to the fuselage. In specified steps, the translational and rotational position of the wing is aligned to the pre-positioned fuselage. The references used here are gap dimensions at the contact surfaces of both components and the three-dimensional position of a reference point on the wing relative to a fixed point on the building site. A large number of people are involved to monitor dial gauges for distance measurements and other measuring devices. Current measurement data is communicated to the control station by voice and must be converted into positioning operations by the operator. This requires maximum concentration and many years of experience. The process can take several hours depending on the current geometric deviations of the components. The same applies to the joining process of the front and rear fuselage sections of an aircraft, which is studied in more detail in this research work. Both sections are about 20 m long each. In the joining area, both the outer hull and the cabin floor must be joined together with narrow tolerances. At the same time, strict specifications for the straightness of the entire external structure must be observed.
With manual measurements only a partial documentation of the joining process is feasible. Results are mainly documented in the joined state and reasons for possible additional work during assembly cannot be reliably traced. Both scenarios show the need for novel sensor concepts and their uniform linkage in the assembly process, to allow for recovering spatial and temporal correlations. For this purpose, it is important to collect data in real time and to bring together all information that can be accessed at all locations relevant for process control. Furthermore, they can serve as a basis for the control of automated positioning systems. IoT technologies are in focus as central building blocks, as they allow straightforward connection of a wide variety of sensor components.

1.2 State of the Art

This research focuses on positioning large components for manual assembly tasks based on measurement data from connected modular sensor components. Two basic approaches can be distinguished here, which are also used together in some cases - local and global measuring systems. Local sensor systems are specialized for a specific measurement task in a narrow spatial environment. They usually do not relate to all dimensional references defined on the component. Global measurement systems, on the other hand, are capable of measuring all relevant dimensional references of the components and systems involved in a large volume.
For component positioning in large volumes, measuring systems such as laser trackers, tachymeters, photogrammetric systems, and indoor GPS have become established in the industrial sector [1, 2]. With this, measurement uncertainties of up to 0.1 mm can be achieved even for component dimensions larger than 20 m, which has proven to be practicable for an overall view of

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the geometry of a large construction site. In practical use, however, the line of sight between the measuring system and the measured object, which is always necessary, is a disadvantage. Human error-proneness or unplanned interruptions are further reasons for occurring process disturbances [3, 4]. In addition, it is often difficult to record gap dimensions and distances between components directly without auxiliary constructions.

At these points, locally measuring systems can be used advantageously. Currently, these are often distance gauges, feeler gauges, spirit levels and other gauge setups that must be read manually and evaluated by experts. At the same time, a large number of already digitally operating sensors exists that can take over these tasks. Dial gauges transmit current measurement data via a Bluetooth interface and inclination sensors provide high-precision information on the current component alignment via wired interfaces. Research shows how sensors can be standardized and energized over time using smart sensor nodes and make their data effortlessly available to a central system [5, 6, 7]. Here, network architectures based on the MQTT or OPC UA protocol are increasingly used for machine-to-machine communication in the industrial environment [8, 9].

If it is necessary to locate the locally measuring sensors only roughly, e.g. for reasons of process safety, less precise systems can be used in many cases. This is the case when measuring positions on the component differ significantly and correct assignment of the measurement data must be ensured. Thus, for measuring in large volumes, the indoor GPS system of Maisano et al. [10] is compared with a Mobile Spatial co-ordinate Measuring System (MScMS) based on ultrasound and high frequency signal transmission. In MScMS, distances are determined using the time-of-flight (ToF) method using distributed, stationary ultrasound transceivers and a mobile measurement probe. In the measuring range below 10 m, an accuracy of up to 5 mm can be achieved.

In the low-cost range, inertial sensor-based measurement (IMU) systems are also of interest for tracking objects in large volumes [11]. The infrastructure- and reference-less sensors often appear in combination with other position sensing systems [12, 13]. For example, Manon Kok et al. [14] present a sensor fusion approach for indoor positioning. Using an IMU and ToF measurements from 10 receivers of an ultrawideband system, accuracies in the single-digit centimeter range are achieved in a volume of 8 x 6 x 2.5 m^3. Peng et al. [15] describe an arrangement of local measurement systems for automated assembly of large components. Based on laser distance sensors, inclination sensors and light barriers, a rough positioning of two components is performed. Using two additional position sensitive detectors (PSD), fine positioning is then carried out and achieves an accuracy of up to 0.5 mm. However, the sensors are permanently mounted and wired, so that flexible handling is not possible.

For an accurate evaluation of the effects of local measurements on the planned assembly process, the fusion of all available measurement data is required in some applications. M. Huber et al. [16] show an approach, which merges all measurement results into one overall result by means of Kalman filters according to their measurement uncertainty. They examined the approach on the demonstration setup shown in this research.

1.3 Solution Approach

The joining and manufacturing tolerances in structural assembly require high precision in execution. When handling the large components, various reference dimensions must always be checked and related to each other. Positioning and measuring processes are therefore carried out iteratively to achieve the desired final state. The research work describes a solution to meet the high demands of fuselage alignment in final aircraft assembly. For this purpose, a new sensor concept and its uniform networking in the assembly process are presented. Precise inclination sensors and alignment sensors are used, which can measure a three-dimensional position deviation of a flat structural component in relation to an external reference. The sensor systems are used to align the airplane cabine floor, which is referenced via its seat rails that later hold up the seats.

A central component of the developed solution is an IoT gateway, which allows the easy connection of a wide variety of sensor components. Local sensor technology is accessible via standard interfaces and data preprocessing steps can be performed. The sensor data is acquired in real time, pre-processed on the IoT gateway, information is merged and visualized for process control. The presented sensor concept is the basis for the control of automated positioning systems.

To evaluate a strategy for automated control of the positioning system, a demonstrator was developed that can be adjusted in six degrees of freedom using linear axes. A corresponding kinematics simulation is used to perform alignment and positioning based on the measurements. Experiences from the investigations on the developed technology demonstrator illustrate the results with realistic measurement data. The result shows how digitalization, decentralized data acquisition and visualization of the processes can significantly simplify the complex fuselage joining process.

2 Methods

2.1 Application scenario

The selected application scenario adresses the joining of front and rear fuselage sections of a passenger aircraft. The task is to achieve the best possible balance between different geometric requirements:

1. Straight outer skin of the aircraft for good flight characteristics and low fuel consumption,

2. Flatness of the cabin floor and high fitting accuracy of the already installed internal structures (seat rails).

3. Gentle fit (penetration) of the outer skin in the joining area.

Both sections are picked up independently of each other on mobile transfer platforms (Figure 1). These have four positionable support points each, so that free positioning of the sections in all spatial directions is possible within mechanical limits. The geometry of the aircraft fuselage is automatically recorded during the joining process by measuring reference points using two laser trackers (global measuring system). Further tools are used for the precise joining of the outer skin, which are not considered in detail in the current scenario. This is where future work will start.

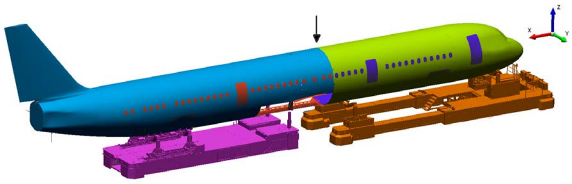

Figure 1 Positioning aids for the front and rear aircraft sections

The focus of this work is on the metrological integration of the cabin floor. So far, the seat rails of the floor were evaluated as reference geometry using manual measuring equipment and gauges. By replacing these with networked sensor systems, current information on the inclination and alignment of the seat rails and the distance between the two sections, can be continuously recorded and used directly for positioning. All reference points on the aircraft are defined in a body-fixed coordinate system. Its x-axis runs along the longitudinal axis of the fuselage against the direction of flight, the y-axis to the right (starboard) and the z-axis upward. The coordinate origin is located in front of the cockpit.

In a first assembly step, the cabin floor of the rear aircraft section is aligned horizontally in two axes (x and y) via the four associated support points. The z-axis of the aircraft coordinate system then points in the opposite direction to the gravitational force. The section remains in this position during the joining process. Only the front section is moved then. Here, too, the first step is the horizontal alignment of the cabin floor in the x and y axes, followed by an adjustment of the rotation about z and the translation in y and z. The last step represents the actual joining process along the x-axis (Figure 2).

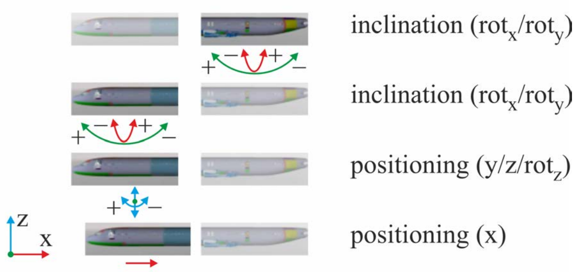

Figure 2 Steps for alignment and join up of front and rear section

The positioning system is controlled manually and must compensate for the geometries inside (local measurement) and outside (global measurement) according to the specified tolerances. In view of the size of the components and assembly equipment, a central recording and processing of all currently measured values is desirable.

2.2 IIoT-Gateway

The metrological monitoring of the positioning of the cabin floor requires a compact and mobile system design. The joining process comprises various working steps. Sensor equipment should not obstruct the working area and should not conflict with safety at work. Therefore, the required size must be minimized and cable connections avoided. Furthermore, the technical basis for the acquisition of the sensor data should be able to be flexibly to meet new requirements. An IIoT gateway developed by the Fraunhofer IFF (Figure 3) is a central component for solving this challenge. It allows the simple connection of a wide variety of sensor components with different interfaces and protocols. The gateway is able to collect data from a large number of distributed sensors and make it accessible for diverse applications.

Figure 3 Gateway with attached sensors

Up to six of 50 predefined sensors, actuators and connectors can be connected to the sensor box. Connected sensors can be operated via a plug and sense functionality. A connected sensor or actuator is automatically recognized by the sensor box and and measured values are immediately available. This works by storing interface-specific details and special features in an application layer hidden from the user. The configuration (e.g. sampling rate or event callbacks) can be adjusted via a web UI. The gateway has sufficient computational power to perform preprocessing tasks such as smoothing, aggregation, filtering or more complex application-specific functions. Such application scenarios are becoming increasingly important, because data can be processed where they are generated and edge computing methods can be applied [17, 18]. Subsequently, the information can be transferred to a server. The application is time-critical. Therefore, care must be taken to ensure low latencies. In the current approach, the sections are initially positioned manually and later, if necessary, automatically. Therefore it must be ensured that the information arriving

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at the server does not exceed a certain age. Two principles must be implemented for this requirement: the availability of real-time stamps and the fastest possible transfer. Lightweight IP-based transmission protocols that follow the publish-subscribe model are particularly well suited for the latter. A prominent representative is MQTT (Message Queuing Telemetry Transport), standardized as an open, royalty free protocol by OASIS [19]. The protocol is widely used in IoT networks, is easy to use and there are numerous client libraries for different programming languages (Figure 4).

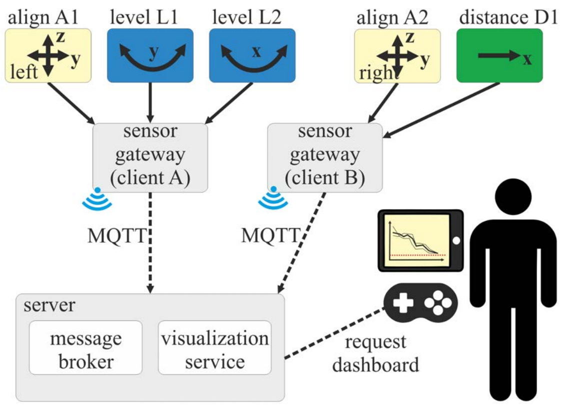

Figure 4 Communication structure

The generation of real-time stamps is ensured on the gateway by the presence of a real-time clock, which synchronizes with the server via time synchronization mechanisms.

2.3 Sensor technology for positioning

In corresponding preliminary work, three different sensor types were identified to perform the alignment: leveling sensors, alignment sensors and distance sensors (Figure 6).
Leveling sensors measure the current angular position of the seat rails relative to the earth's gravitational field. The most important criterion for dimensioning here is the tolerance specification from the aircraft design data. The permissible angular deviation of the seat rails in the joining area is approx. 400 µm/m along the aircraft axis. In order to prove this reliably, a sensor was selected whose measuring element is based on a pendulum that can oscillate freely between two electrodes. Depending on the inclination of the system, the pendulum changes its position and the capacitance between the pendulum and the electrodes. This change is evaluated digitally and provides an angular measurement between ±5 ° with a typical measurement uncertainty <20 µm/m. Each sensor is mounted on a beam 1.5 m long with two defined contact points (Figure 5).
The zero position (horizontal position) must be determined in advance by means of an envelope measurement. It is taken into account as a reference value for subsequent measurements. Both sensors are connected to the IoT gateway via an RS485 interface. The gateway synchronizes the asynchronously arriving measured values of the leveling sensors by means of a heuristic that exploits the internal time stamps of the sensors. Due

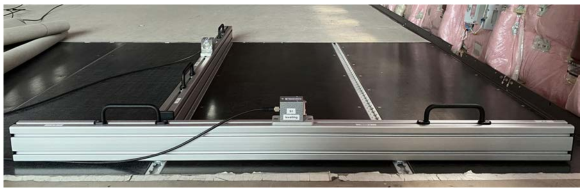

Figure 5 Leveling sensor on cabin floor

to the mechanical measuring principle, the sensors tend to oscillate when the position changes. Therefore, a moving average over 2 s measuring time (=20 measured values) was implemented as a pre-processing step on the gateway, with simultaneous evaluation of the fluctuation range. If the fluctuations are outside the specified range, the corresponding data packets are enriched with the status 'unsafe'. The data packets are then provided with a real-time stamp and published.
Two **alignment sensors** were dimensioned in order to be able to measure the alignment of corresponding seat rails of both sections to each other, i.e. the deviation in y and z. Each sensor consists of two independent components: a laser beam source and a projection screen mounted along a seat rail. The laser beam source is manually adjustable in two axes and allows the laser beam to be aligned parallel to the seat rail.
The projection screen is observed by a camera permanently mounted on it, which measures the position of the laser light spot relative to surrounding reference LEDs and outputs the deviation in two axes relative to a pre-calibrated center (Figure 6).

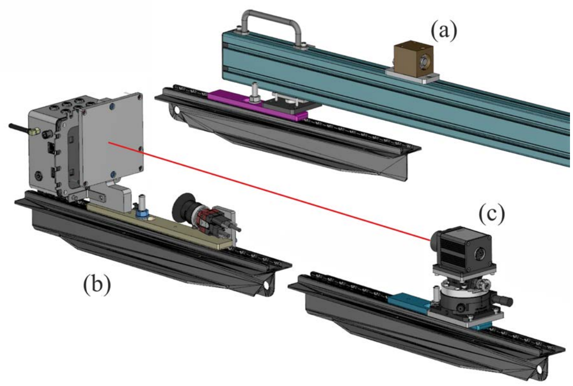

Figure 6 Leveling (a), alignment (b) and distance sensor (c)

This deviation is calculated directly on the gateway in real time and the result is sent to the server. For this purpose, a center of gravity search is used to find the reference LEDs and the additional laser point in the camera image. The next step involves the elimination of interfering influences (e.g. scattering and reflections), a self-calibration of the system and a plausibility check. The position of the laser point is calculated by projecting the image coordinate onto the plane formed by the reference LEDs.
For this purpose, a calibration is performed for the camera in advance, in which all parameters describing

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the geometrical imaging process are determined. First, the laser and projection screen are mounted on a seat rail of the front section with the largest possible distance. Mechanically, this ensures that the components can be placed on the holes in the seat rail in a repeatable manner. The laser beam is then aligned so that the deviation from the center reference measured on the projection screen is zero in both axes. As a result, the laser beam takes over the direction of the front seat rail.

By moving the projection screen to the corresponding seat rail of the rear section, close to the joint, the misalignment of both seat rails can be measured directly. Two alignment sensors are mounted on the outer seat rails on the right and left. Due to the process, a measuring range of ±50 mm in the y and z axes was required. Tolerances to be observed for the joining process resulted in a permissible measurement uncertainty of ±0.1 mm. The comparatively large measuring range required led to the choice of a camera-based measuring principle. Comparable sensor systems use a PSD element (position sensitive device) to measure the position of the laser dot directly. However, these are only available for significantly smaller measuring ranges.

While the projection screen for the right sensor (starboard) is mounted close to the joint, the second projection screen on the left is mounted as far away from it as possible. In this way, the rotation about the z-axis of the front section, which is also to be detected, is represented in the form of a measured deviation of the y-axis. For the calculation of the rotation position, a **distance sensor** is required to get the distance between both projection surfaces along the x-axis.

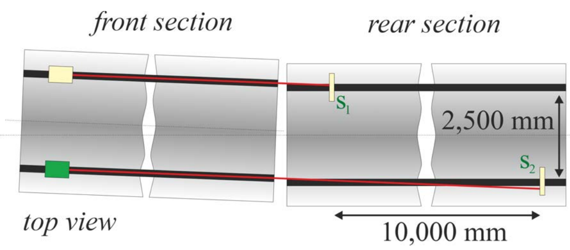

Figure 7 Calculation of allowed inclination angle and x-distance

For a direct measurement of this value, the laser beam sources were replaced by laser distance sensors. These operate according to the measuring principle of phase comparison measurement and ensure a maximum linearity deviation of ±1 mm up to a distance of 20 m. With the distance conditions present here (distance approx. 10 m), the rotational deviation about the z-axis can thus be determined to approx. ±10 µm/m (Figure 7).

After the final joining step of the fuselage sections (x-alignment), connecting elements for reinforcement are inserted into the front and rear seat rails.

For this, the maximum position deviation in the x-direction must not be greater than 150 µm. This cannot be reliably measured with the distance sensors integrated here. Therefore, in the last step of the joining process, from a distance of approx. 5 mm between the seat rails of the front and rear sections, the remaining distance is determined and delivered using manual measuring equipment.

2.4 Actuators and inverse kinematics

For the evaluation of the proposed alignment concept, a stand-alone demonstrator was built to represent the front and rear fuselage shells. A direct integration of the sensor system into the aircraft assembly was not possible without disturbing the ongoing production. Nevertheless, findings for modeling and controlling the kinematics should be transferable to the real process.

As a demonstrator, a frame-based device was designed and built that replicates the principle of section assembly with all the necessary degrees of freedom (Figure 8). Relative to a fixed outer frame (representing the rear fuselage section), an inner frame (front fuselage section) can be positioned by several motor units. Both, the already described sensors for the alignment of the cabin floor and reference points for a global measurement by means of a laser tracker can be applied.

The dimensions of the demonstrator are: length 2200 mm, width 900 mm, height 660 mm.

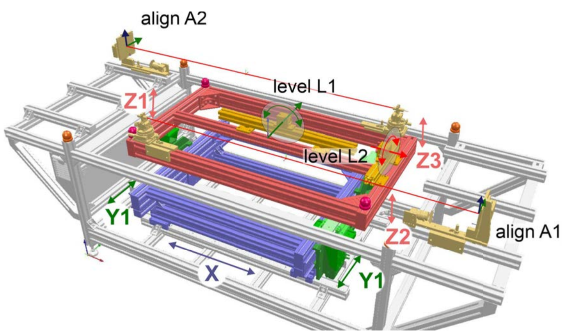

Figure 8 Demonstrator: positioning axes and sensors

The inner frame has six independent positioning axes (active joints) and therefore a comparable number of degrees of freedom as the mobile platform of the front section used in the assembly line. Ball joints and other compensating mechanisms (passive joints) allow very flexible translation and rotation of the inner frame. The individual axes are controlled by a PLC. Measurement signals and control commands are exchanged via MQTT in a common network with the sensor box.

For the feedback of the sensor information into a control signal of the positioning axes, the entire kinematic chain was mapped in the Coppelia Robotics software (Figure 9). A hierarchical model structure summarizes all relevant mechanical degrees of freedom and their static connections, starting from a base point.

A position and orientation deviation for a target point defined on the inner frame (target) is calculated directly from the current sensor data. Based on the difference to a target position, the inverse kinematics generates control commands for the six positioning axes (Figure 8).

The distance sensors described in the concept were not implemented in the demonstrator. Due to the compact dimensions, the rotation around the z-axis could not have been determined reliably. Instead, one of the alignment

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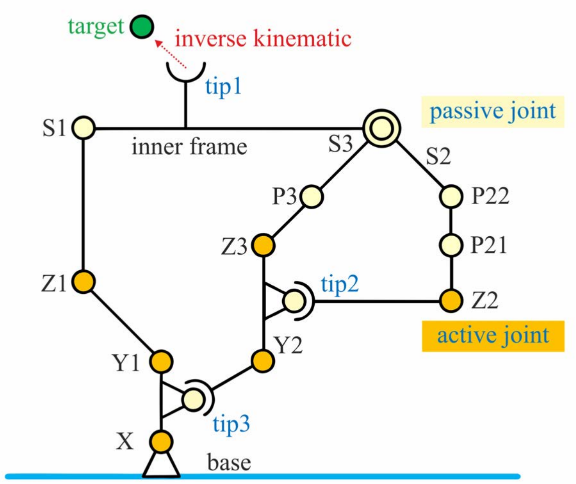

Figure 9 Demonstrator: kinematic chain

sensors was set up in the opposite direction. This also allows the reliable separation of z-rotation and y-translation.
A Leica AT901 laser tracker was available as a global measurement system for the experiments at the Fraunhofer IFF. Nests for positioning the reflector spheres were attached to both the outer and inner frames and integrated into the kinematics model.

3 Results

3.1 Experimental setup

To confirm the chosen concept for the alignment, the demonstrator was physically built and equipped with sensor technology (Figure 10).

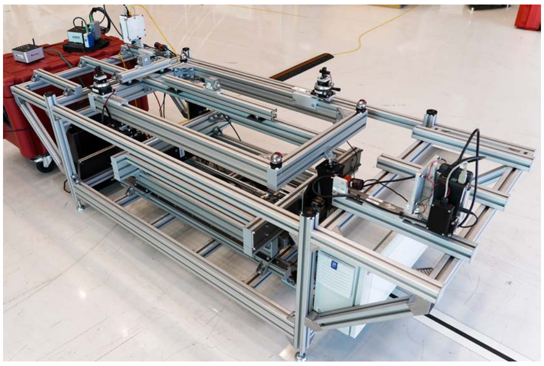

Figure 10 Demonstrator for technology test

With the help of the inclination sensors and a long beam, the guide rails of the outer frame (rear section) were first aligned horizontally in the x and y axes. The reference points were selected so that they correspond to the later measuring points for the y and z deviation (Figure 11). This avoids having to align the guide rails parallel and in alignment with high precision over the entire setup. The distance in the y-direction between the guide rails was adjusted to the nominal dimension by means of a laser tracker. The four corner points of the inner frame were already aligned in one plane during manufacture and the guide rails were checked for parallelism and nominal distance.

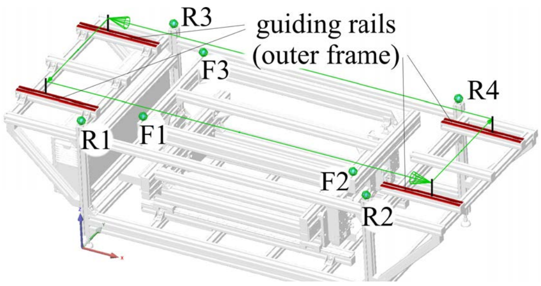

Figure 11 Outer frame and reference points

Measurements were carried out with the sensor gateway and the sensor setups corresponding to the joining process in various tests. For this purpose, the inclination sensors were placed on the inner frame (front fuselage section) and the lasers of the alignment sensors were aligned with its guide rail. By moving the camera systems of the alignment sensors to the corresponding extension of the guide rail on the outer frame, the remaining offset of the guide rails is measured (Figure 8).
Measurement data was collected and forwarded to a server via the associated IoT gateways. The simulation tool retrieves this data from the server and directly controls the positioning axes. The process is executed iteratively and determines the relative movements to be executed in each case. Since the measurement data is not acquired synchronized and is subject to indefinite latencies due to the transmission via WIFI, the time stamp carried is always decisive for the evaluation of the data.
Positioning in the x-direction is not taken into account in the test, since the joining process takes place along this axis. The positioning axis remains in a fixed position. As already described, a distance sensor is not used. It was replaced by a laser spot generator.

3.2 Experiments with local sensors

Starting from randomly selected positions of the positioning axes, the automated alignment process was started. This initially compensates for the angular position of the inner frame using the inclination sensors and then for the remaining deviations of the rotation around the z-axis and the translations in y and z.
The associated diagrams show that already in the first step the deviations are largely compensated. This behavior was to be expected, since the geometry model on which the inverse kinematics is based agrees well with the real structure. The subsequent steps further compensate the model errors and lead to a minimization of the alignment errors detected by the sensors (Figures 12, 13). However, the alignment does not converge at a single stable value. Depending on the initial situation, different deviations remain, but they are within the expected tolerances. For alignment these are ±0.3 mm and for angular position ±0.001°.
A single positioning step takes about 5 seconds. The

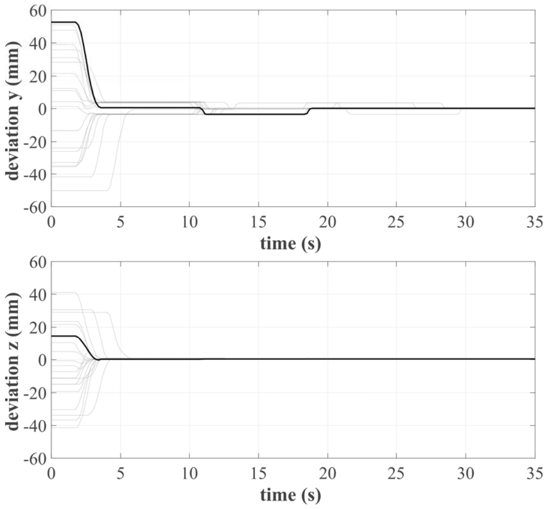

Figure 12 Sensor align A2

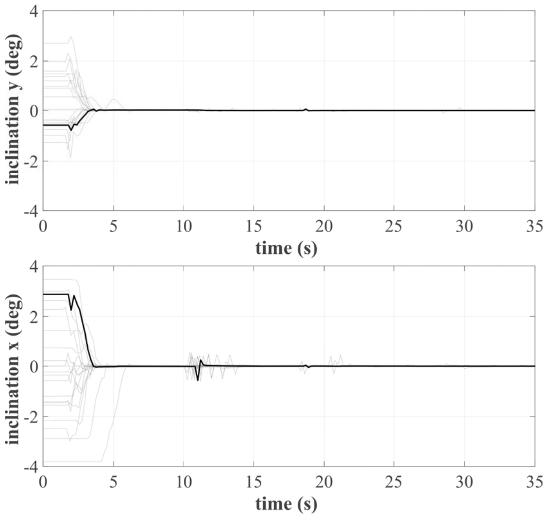

Figure 13 Sensors level L1 and L2

reason for this are the inclination sensors used, which require several seconds after a position change to reduce oscillations of the detector. Only after reaching a predefined standard deviation of the measured values over one second, the next step is released.

3.3 Experiments with global sensors

Nests for the reflector spheres of a laser tracker were applied for the alignment tests using a globally measuring sensor system (Figure 11). The target positions of the nests envisaged in the design can only be achieved approximately on the demonstrator due to construction deviations. However, these deviations are also present on the aircraft and must therefore always be taken into account.

The position of the coordinate system for the measurements was determined by the four outer points R1 to R4 using a bundle adjustment. During the alignment process, the three reference points F1 to F3 were measured on the inner frame before each iteration. The data from the laser tracker was also made available to the data network via an MQTT interface.

The tests carried out starting from different starting positions also showed convergence here within three to four iterations. The remaining deviations of the three measuring points were up to 0.5 mm. The measured values of the local sensors recorded in parallel showed deviations in the alignment of up to 1.0 mm. This can be explained by the structural deviations of the demonstrator. Only the fusion of local and global measurement data, taking into account the measurement positions and measurement uncertainties, leads to the best possible alignment of the inner frame [16].

4 Discussion

The technical concept for the integration of networked sensors using IoT technologies in the fuselage section assembly was successfully validated. By means of a demonstrator, it was possible to show that the joining process can be efficiently supported. Starting with the precise recording of currently existing deviations and their provision in a common data network, it is possible to generate active feedback into the process through automated control of the positioning axes. Simultaneously, the data can be visualized and stored centrally on a terminal of the control station and, if necessary, merged with other previously recorded measurement data. This gives the machine operator the possibility to influence the joining process in a targeted manner, taking into account all available information. A corresponding simulation tool could provide valuable information for manual control in the future. Time-consuming manual inspection tasks are reduced to a minimum.

The demonstrator tests prove that the speed of the joining process can be significantly increased by using networked sensor technology together with automated alignment and positioning steps. The use of inclination sensors with more favorable vibration behavior could further shorten the overall process. Future work is focused on integrating the inspection tasks on the outer hull of the fuselage. Furthermore, the fusion of all available measurement data under consideration of the respective measurement uncertainties is an important task. A completely automated joining process is not planned from the current point of view due to the large number of boundary conditions to be taken into account. However, a simulation of the kinematic processes with prediction of achievable quality criteria could be an important building block.

Acknowledgements

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