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## Metrology assisted assembly of airplane structure elements

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### Abstract

Geometric deformations in large components like airplane shells caused by e.g. gravitation influences have to be compensated before assembly. The research objective is to develop a metrology assisted robot based assembly system that detects deformations and compensate them through force controlled movements of the robots. The determination of robot compensation movements uses a model of the components deformation behaviour. For the determination of the model parameters an identification process is developed, which uses samples of the real component deformation behaviour caused by defined external forces to approximate the parameters (e.g. stiffness) of the component.

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### 1. Introduction

Conventionally, the production of large products is characterized by small lot sizes, consumer specific products and high prices. In most cases this kind of production includes a high proportion of manual work. A fully automated production of individualized products is difficult to implement, because the required huge production systems are in most cases specifically designed, i.e. for only one product or component. These systems are cost-intensive and, under consideration of the small lot sizes, not efficiently applicable for all assembly tasks [1].

Because of the large dimensions and proportionally small tolerances, standard production systems (like industrial robots) can not reach the necessary production requirements. A method to increase the precision of standard production systems is to use metrology systems as assisting units that can detect production deviations and compensate them through adjustments of production parameters.

One field where such metrology assisted production system could increase the production efficiency is the airplane industry. The airplane structure consist of many large components, which have to be assembled to the final airplane structure. The assembly of these large, flexible components is a complex task, as the parts have to be positioned precisely and need to be untwisted before they can be assembled. Traditionally fixed jigs are used to guarantee the correct shape of the products. Nowadays, more and more programmable jigs and robots in combination with large volume metrology systems are used to increase the flexibility of the production systems. These systems operate on the principle of positioning by measurement. The metrology systems measure production deviations, like geometric deformations, and the control unit determines compensation movements of the kinematics.

However these compensation process can not be processed automatically, as the reaction to external forces of each part is unknown and can not be planned in advance. Models to describe this components behavior which are needed for an automatic control, do not exist yet. The use of the flexibility of a robotic system in combination with metrology systems, as a

programmable jig for a more efficient, automated assembly process [2], needs new control algorithms which are suitable for an automated control without manual intervention by workers. This paper describes the development and implementation of positioning and force torque sensors, which are needed for a metrology assisted robot based positioning and untwisting process of airplane structure elements.

## 2. Description of the airplane structure and the assembly process

The fuselage of modern airplanes is constructed with shell elements. These shells consist of the skin panel (planking) and the inner framework, which is build with stringers, clips and frames (see figure 1). The mechanical advantage of this structure is the use of the panel for the absorption of the loads induced during flight. [3]

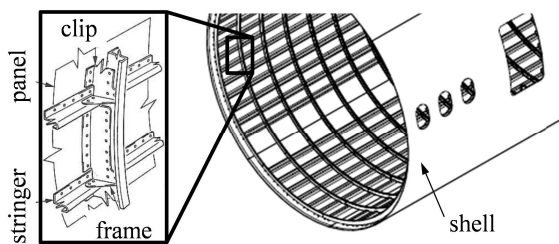


Fig. 1 Design of an aircraft section (based on [3], [4])

For the production of the fuselage, the hull is divided into several sections. The sections are built by using a variable number of shell elements, which are joined with rivets. The dimensions of the sections depend on the airplane. For a typical plane the length varies between nine and eighteen meters. Last-generation airplanes are equipped with a hull structure consisting of aluminum or aluminum alloys. For this material the parts are built with standard forming processes followed by milling processes. Airplanes currently being developed consist of fiber composite materials like CFRP (carbon fiber reinforced plastic). [4] This paper focuses on the assembly of CFRP sections.

### 2.1. Production and assembly of an airplane section

The production process starts with the layup of the skin panel by pasting preimpregnated carbon-fiber on a forming tool. For the impregnation of the fibers special resins are used. These resins build a matrix which connects the single fibers to get a stable structure with a fixed fiber alignment. After panel production the assembly of the section starts. The assembly is divided into three main steps:

1. Stringer integration
2. Shell assembly
3. Section assembly

During stringer integration consolidated stringers are assembled to the unconsolidated panel, which has a diameter

of about six meters and a length of nine to eighteen meters. The shape and geometry of the unconsolidated flexible panel is ensured through a forming tool, that maps the geometry of the airplane structure,

### 2.2. Shell assembly

The challenge in shell assembly is to untwist a large, deformed panel (mainly due to gravity) and to join it unstressed with frames, which stiffen the panel. The joining is done indirectly with clips, which also accommodate gaps between the panel and the frames. The joining technologies for this process are bonding and riveting.

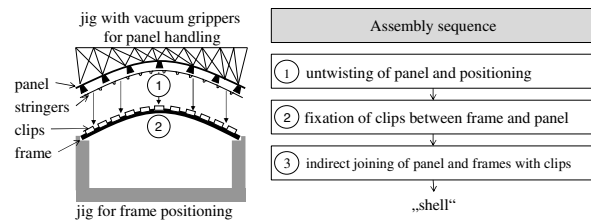


Fig. 2 Classical shell assembly

The panel is set in shape by vacuum grippers, which pull the part against a contour that maps the geometry of the part (on appr. 120m<sup>2</sup>). The vacuum grippers form the upper jig of the assembly station to position the panel to frames, which are mounted in the lower jig of the assembly station (see figure 2). By moving the upper jig downwards, the panel and frames are aligned. After alignment the clips are manually fixed between the frames and the panel for the subsequent joining by riveting.

### 2.3. Section assembly

For the assembly of a section all components have to be aligned. One section consists of four shell elements (left and right side shell, upper shell, lower shell) and the floor grid. To fulfill the tolerance requirements the side shells have to be positioned and untwisted. The untwisting is needed to compensate for deformations of the shell (mainly due to gravity). A manipulator system has been developed for this process [5] and is already used in series production. The side shells are grasped by vacuum and mechanical grippers and positioned by several linear actuators. The process is monitored by several force/torque sensors and global and local measurement systems. As the product does not fit to the shape tolerances, the actuators can not reach the desired grasping point exactly. Also the positions of measuring points are only estimations. An iterative process determines the deviations between target and desired position and minimizes the residual [5]. The control of the station is done automatically, as long as force limits are not exceeded. In case of exceeding forces the process needs to be continued manually, as data from force/torque sensors is not viable for automatic control.

The principles of this semi-automatic process in section assembly are being used and enhanced for the control of an

automated position and untwist process, using a robotic production system which is proposed in this paper.

### 3. Robot based positioning and untwisting process

The goal of research is to develop an automated metrology assisted robot based positioning and untwist process for airplane structure elements. With the developed process the flexibility of the airplane assembly may be increased by replacing fixed jigs with programmable robot systems.

The task of the positioning and untwisting process is to compensate for geometric deformations of the airplane panel mainly caused by gravity or other influences. Therefore several robot kinematics have to grasp the panel and compensate the geometric deformations through compensation movements. The main challenge is to determine the movements of the kinematics to compensate for geometric deformations. The compensation movements are essential because each panel has different geometric deformations and a static process control can not react on these changing production requirements. The controlling system has to identify the current process state, it has to determine the current geometry of the skin panel and identify geometric deformations in combination with the loads and positions at the kinematics grasping points. Based on this information the system has to make decisions how to compensate for the detected deformation and modify the systems behavior for a automatic adjustment of the components shape[6].

A controlling system that performs these three actions of identification, defining new targets and modification of the systems behavior is called a self-optimizing system [2],[6]. The self-optimizing system is an expansion of the basic process control and is able to automatically adjust system targets in order to achieve the required results. The developed automated positioning and untwisting process uses the principle of self-optimization to compensate for the geometric deformations of the airplane panel.

#### Research platform

The research platform consist of a robotic cell with Kuka and Reis robots. The cell is equipped with an iGPS (indoor Global Positioning System) measurement system (measurement uncertainty  $\pm 150\mu\text{m}$ ) and several local sensors like time-of-flight (TOF) cameras or cameras for machine vision. The experimental setup for the positioning and untwisting process consists of two industrial robots and one downsized CFRP panel, supported by an aluminum frame. To enable deformations, the panel is fixed bearings in the top and movable bearings in the bottom of the aluminum frame (see fig. 4). In the future the aluminum frame will be replaced by flexible kinematics, which are currently developed in the project [7]. The test component is a downsized CFRP panel (stringers already integrated) in dimensions of 1.7 m x 2.1 m (see figure 3).

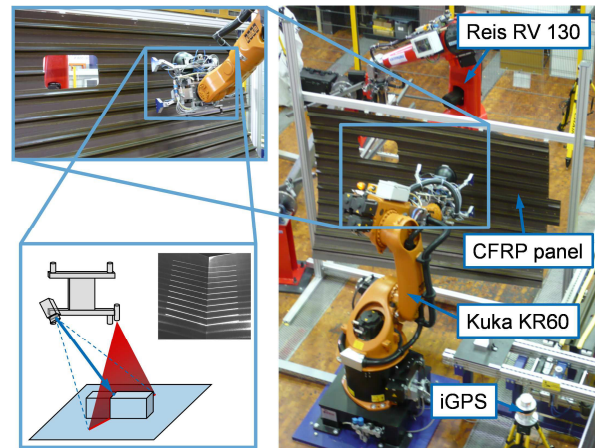


Fig. 3 Positioning and untwisting test stand

A key task for the automated positioning and untwisting process is to enable a robotic system, to compensate geometric deformations of the panel. Therefore external forces are needed, that are applied on the panel by the robot kinematics. As mentioned before the manipulator system of the section assembly uses positioning information as compensation parameter. That means, that the system calculates from the measured geometric deformations compensation movements based on geometric information. Force-/torque information are used as controlling units to avoid damage to the components. For a more efficient compensation process a force control is implemented to compensate the geometric deformations through defined forces of the kinematics.

### 4. Force controlled geometry compensation

To enable force controlled movements, the robot needs knowledge of the exposed force on the grasped component. For the force measuring a 6D force-/torque-sensor is integrated into the handling tool of the robot. The measurement resolution of the sensor is  $\pm 0.125\text{N}$  in x-, y-direction,  $\pm 0.3125\text{N}$  in z-direction and  $\pm 0.0125\text{Nm}$  for torque measurement. The tool consist of a vacuum gripper equipped with four suction cups. The sensor is placed between the vacuum gripper and the robot flange (see fig. 4).

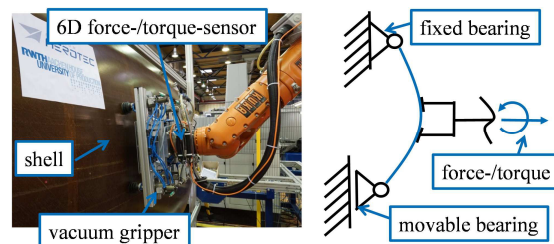


Fig. 4 Configuration for force controlled geometry compensations

With the mentioned sensor configuration, the sensor measures the exposed forces and torques by the robot and the

weight force resulting by the vacuum gripper in dependence of the actual orientation of the robot. To determine the exact forces at the grasping point or TCP (Tool Centre Point) the measured forces have to be transformed to the TCP. Therefor the force distribution has to be described mathematically. Equation (1) and (2) describe the force and torque balancing of a static system. The variable “F” and “M” describe the forces and torques in a closed system. The parameter “r” characterizes the lever arm of a force applied on a referent point for the torque balancing. The force control can be described as a static system, because the compensation movements are slow and only in a range of millimeter.

$$\sum_{i=1}^n \vec{F}_i = 0 \tag{1}$$

$$\sum_{i=1}^n (\vec{r}_i \times \vec{F}_i) + \sum_{i=1}^n \vec{M}_i = 0 \tag{2}$$

The application of these equation on the force control unit needs the knowledge of the geometric structure shown in figure 5. The transformation matrices H describe the positions between the vacuum gripper (TCP), the force-/torque-sensor and the robot base. The transformation matrices  ${}_{Base}H^{TCP}$  and  ${}_{Base}H^{Sensor}$  describe the positions of the vacuum gripper and the sensor to the robot base. These transformations change during the process in dependence on the robot movements. The other transformations are static and do not change during the process.

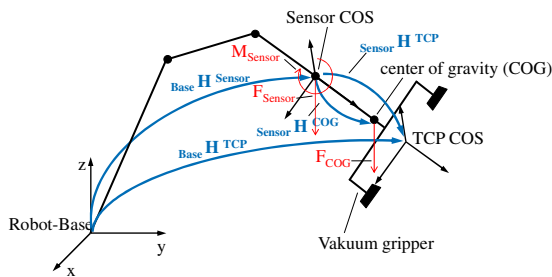


Fig. 5 geometric structure of the force control unit

The force/ torque balancing equations based on the TCP are show in equation (3) and (4). The balancing is based on the TCP because these forces describe the exposed forces on the panel.

$$\vec{F}_{TCP} = -\vec{F}_{COG} - \vec{F}_{Sensor} \tag{3}$$

$$\vec{M}_{TCP} = -\vec{r}_{Sensor} \times \vec{F}_{Sensor} - \vec{r}_{COG} \times \vec{F}_{COG} - \vec{M}_{Sensor} \tag{4}$$

- $F_{TCP}$  = force vector at TCP
- $M_{TCP}$  = torque vector at TCP
- $F_{COG}$  = weight vector at COG (center of gravity)
- $F_{Sensor}$  = measured force vector at Sensor
- $r_{Sensor}$  = distance vector between TCP and Sensor
- $r_{COG}$  = distance vector between TCP and COG

With these equations the system could calculate the forces and torques at the TCP during the process under consideration of the weight vector of the handling tool. A necessary condition is, that all forces and torques are described in the same coordinate system. Therefor all force and torque vectors are transformed into the base coordinate system of the robot. Another condition is that the weight of the tool and the transformation matrices are known. Some of these parameter can be read directly from the robot control, like the position of the TCP and the position of the sensor. Other parameters like the COG (center of gravity) or the weight of the tool have to be identified during a calibration routine. In this routine the robot performs a slow movement in open space without contact to a component. During this movement the measured force, torque and robot position values are stored. With these information a numeric algorithm calculates the unknown parameter with the condition, that all forces and torques during the calibration movement at the TCP have to be zero [8]. The results of this calibration routine are shown in figure 6. The graph shows the force values during the calibration movement in Z direction of the TCP coordinate system with the determined system parameter (‘with calibration’) as a constant line at value 0, which means that the calibration routine was successful.

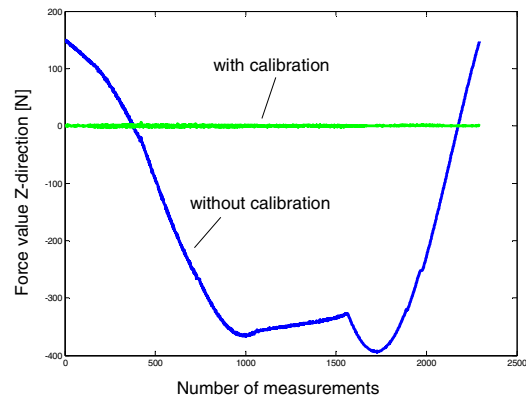


Fig. 6 force values in Z-direction

Through the mathematical description of the force balancing in combination with the calibration routine, the system is able to determine the forces that are exposed on the panel geometry during the positioning and untwisting process. Based on these information a regulation routine is able to move the robot towards the panel with the goal to reach the necessary compensation force at the grasping point.

The force controlled positioning and untwisting process could only compensate geometric deformation if these deformations are known. The deformation have to be identified through a measurement system that scans the surface of the panel and compares the measured geometry with the planned product geometry.

## 5. Optical scanning system

The identification of the panel geometry is a main part of the positioning and untwisting process. Therefore a 3D scanning system is used to measure the surface of the panel. This system uses an optical light section sensor carried by an industrial robot and tracked by an iGPS large volume metrology system.

A light section sensor is an optical laser based metrology system. These systems use the interaction between the laser radiation and the measurement object to identify the searched measurement parameter. In the case of the light section sensor the system consists of one or more cameras and a laser source aligned in a fix mechanical connection. The laser source projects a laser plane in the space, which origin is defined in the center of projection. When the laser plane is cut by an object in space, the laser light is reflected by the surface profile along a line. This reflection on the profile line is detected on a camera sensor as a two-dimensional line and contains the geometric information of the measured object (see fig. 7) [9]. If the geometric relationship between the camera and the laser source are known the height profile of the measured object can be calculated along the reflected laser line through triangulation.

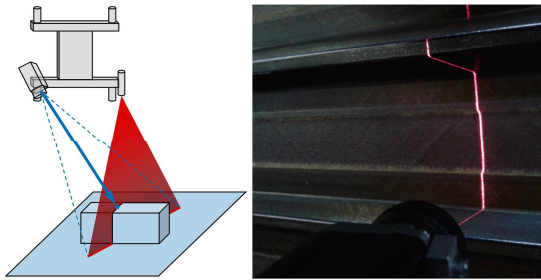


Fig. 7 Reflected laser line as measurement information

To scan the whole panel geometry the light section sensor is moved over the surface of the panel by an industrial robot (RV130). During the movement the system measures in a fixed time interval single height profiles of the surface. These profiles have to be connected in a main or world coordinate system to reconstruct the panel geometry. One method to connect the profiles is to use the position data of the industrial robot as a main reference system. All measurement information will refer to this base coordinate system. However, the relative low positioning accuracy of the industrial robot will lead to a big measurement uncertainty. Therefore, it is more efficient to use another metrology system that decouples the measurement uncertainty from the robot uncertainty.

For the positioning and untwist process an iGPS metrology system is used to measure the end effector of the robot during the measurement movement. This system is able to measure the 6D pose of an object with optical signals. The measurement object has to be equipped with receivers that can detect the optical signals send by several transmitters positioned around the assembly station. The main advantage of this measurement system is, that it can detect several

objects simultaneously in one coordinate system (for more information about the iGPS see [10]).

The principle of the light section sensor to determine the geometric information of a three dimensional object in a world coordinate system is a detailed model, that describes the projection properties of the laser and the imaging characteristics of the camera in a defined reference system. The description of this model and the necessary calibration steps to determine the characteristics of the sensor are explained in [11].

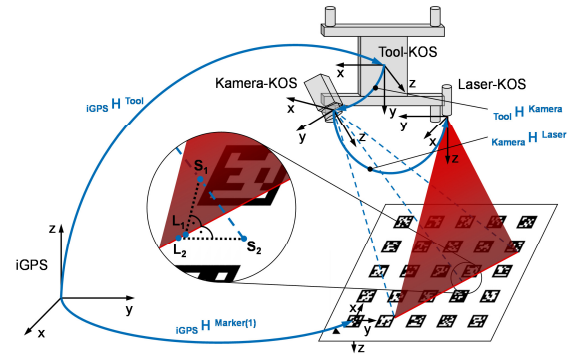


Fig. 8 Calibration model of the optical scanning system

The result of a panel geometry scanning process is a point cloud that represents the surface of the inner panel geometry which is relevant for the assembly processes (see fig. 9). The achieved measurement uncertainty of the geometry scanning system is about  $\pm 0,4\text{mm}$ .

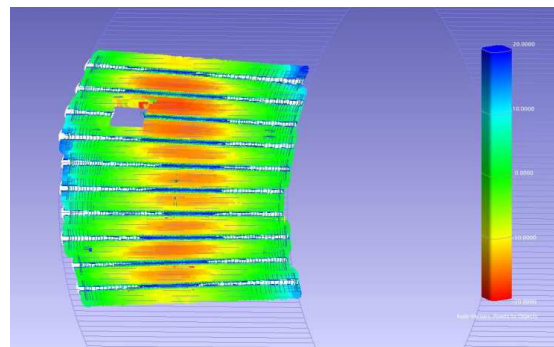


Fig. 9 Measured surface deviation of the panel

The color coding in figure 9 represents the geometric deviation of the measured surface in comparison to a cylinder. The cylinder represents the desired assembly geometry of the component. Based on the determined geometric deformation, the self-optimizing system control has to make a decision how to compensate these deformation through force controlled movements of the robot. For decision making a model is needed that describes the behavior of the panel due to applied forces of the robot. The development of such a deformation

model based on samples of the real deformation behavior is in focus of current research.

## 6. Conclusion

Metrology assisted robot-based assembly systems can replace fixed jigs and increase flexibility of an assembly system. The depicted project concentrates on an automated positioning and untwisting process for airplane structure elements. Whilst the mechanical design of a robot system offers a high level of flexibility, research has to be done to develop new control algorithms which are suitable for an automated process control without manual intervention by workers. The depicted robot based positioning and untwisting process uses force control motions to enable an industrial robot to compensate for geometric deformations without destroying the component. An optical metrology system measures the current panel geometry during the process and in order to determine the geometric deformations.

For an automated compensation of deformations the basic process control has to be extended with self-optimizing process strategies. This approach enables the system to make decisions in order to determine and to reach optimal system targets. Therefore in ongoing research a model is being developed which describes the panel deformation behavior. With this model and the metrology systems as assisting units the self-optimizing process control will automatically compensate geometric deformations by detecting and autonomously correcting panel deformations by the assembly station. Additionally, this assembly method may be suitable for other products and assembly processes, e.g. in rail industry or ship building, where large components have to be flexibly positioned within small tolerances.

## ACKNOWLEDGEMENT

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