Self-Optimization in Large Scale Assembly

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ABSTRACT

Efficiency in aircraft production can be increased by using flexible robotic assembly systems instead of fixed jigs, but the flexibility can only be used in combination with efficient control algorithms. For large components which have an individual deformation, e.g. due to gravity, not only automated but self-optimizing control algorithms are required, which allow an autonomous product-specific adaptation of the systems behavior during assembly. Therefore, models are required in order describe the products behavior to external forces and to adapt the robot motions. Multiple linear regression is presented as an approach to generate a product model based on experimental data. The product model is used to generate robot motion for an automated untwisting process of large components. The depicted approach is being validated at a demonstrator consisting of two industrial robots and a CFRP panel.

Keywords: integrative production; self-optimizing assembly; large scale assembly

1. Introduction

Traditionally, producing companies ensure their competitiveness either by being a mass producer and manufacture many simple and cheap products ("economies of scale") or by producing consumer specific products for higher prices and in small lot sizes ("economies of scope"). Nowadays, this tradition has to be overcome, as customers demand more and more for individualized products for low prices ("mass customization"). To fulfill these growing demands, companies have to decide if they want to use a detailed planning for an efficient production or to minimize non-value-adding planning efforts and make decisions value-oriented on shop floor level.

Current research projects tackle this “polylemma of production” and reduce the dilemma between scale and scope and the dilemma between plan- and value-oriented production planning. One approach to increase efficiency in production planning are self-optimizing production systems, which can reduce planning efforts by a recurring execution of the three actions [1]

1. continuous analysis of the current situation,
2. determination of targets, and
3. adaptation of the system’s behavior to achieve these targets.

That means that planning efforts do not have to be done by a human in advance but can be done by a machine during production. One industrial area, where such a functionality could increase efficiency significantly, is aircraft assembly. The assembly of large, flexible components is a complex task, as the parts have to be positioned precisely and untwisted before they can be assembled. In the past, fixed steel jigs have been used to guarantee the correct shape of the product. Nowadays, more and more programmable jigs and robots are used to increase the flexibility of a production system. But the positioning and untwisting process can not be done automatically, as the reaction to external forces of each part is different and can not be planned in advance. Self-optimizing systems which execute the actions

1. measurement of deformations of a component,
2. decision how to compensate these deformations,
3. automatic adjustment of the components shape, e.g. by a robotic system
are in focus of research, in order to be able to utilize the flexibility of a robotic system for a more efficient, automated assembly process control [2]. Assembly processes in aircraft production which have been identified with a high potential for robotic execution are presented in the next chapter.

2. Description of components and assembly processes

An aircraft structure can be divided into the subassemblies fuselage, wing, horizontal and vertical tail plane (HTP, VTP) and engine [3]. The fuselage is composed of several sections, each consisting of several shells. One shell is made of a panel, several stringers (for axial stiffening), frames (for tangential stiffening) and clips, which join the frames indirectly with the panel (figure 1). Modern production systems have to address the requirements of modern airplanes. The latest developments are airplane constructions made of carbon fiber reinforced plastic (CFRP). Therefore the following description focuses on the production of this new aircraft technologies, e.g. Airbus A350.

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

After manufacturing of the components (tape laying, consolidation, milling etc.) the assembly of aircraft structures can be divided into three main steps:

1. stringer integration
2. shell assembly
3. section assembly

For the assembly of these aircraft structures, large jigs, which map exactly the geometry of the components, are used to assemble the product without too high forces and stresses. These jigs are expensive, product-specific and have therefore only a low level of utilization. For some processes, robots could already replace fixed jigs successfully as a more flexible solution to assemble different derivatives of a product in one station.

2.1 Stringer integration

During stringer integration consolidated stringers are assembled to an unconsolidated panel, which has a diameter of up to 6m and a length of up to 18m. Despite the huge dimensions, the tolerances for positioning the stringers are only within millimeters. To fulfill these requirements there are two different assembly methods. One method is a huge vacuum gripper, which maps exactly the diameter and length of the shell and places all stringers simultaneously at the panel.

For this method different shells require different tools. Changes in product design cause also expensive changes at the tools. A more flexible method for stringer integration is currently in research. In this approach a group of robots handles and positions stringers within given tolerances (monitored by a
measurement system) independently of the curvature of the shell [5]. In this solution the assembly equipment is independent from product design. Thus, in future production lines different shells can be assembled in one station, the utilization of this station can be increased and the costs for the assembly equipment can be reduced.

2.2 Shell assembly

The challenge in shell assembly is to untwist a large, deformed panel (mainly due to gravity) and to join it almost unstressed with frames, which give the final stiffness to the panel. The joining is done indirectly with clips, which can also bridge a gap between the panel and the frames. The used joining technologies for this process are bonding and riveting.

The panel gets in shape by vacuum grippers which pull the part against a contour that maps exactly the geometry of the part (on appr. 120m²). This contour is the upper part of a huge assembly station to position the panel to frames, which are mounted in the lower part of the station (figure 2). By moving the upper jig downwards, panel and frames are positioned. After that, clips are manually fixed at the frames with contact to the panel for the subsequent joining of panel and frames. The resulting product is called “shell”.

![Figure 2. Shell assembly using fixed jigs](image)

Whilst in the existing process all parts (panel, frames, clips) are positioned in large jigs, the mass of steel construction can be reduced by implementing a robotic assembly of clips and frames to the panel. This robotic system does not exist yet and is focus of research of the authors. The work is based on existing, similar assembly processes, e.g. section assembly, in which large components are also handled and of which principles can be transferred to the assembly of shells.

2.3 Section assembly

For the assembly of a section the left and the right side shells have to be untwisted, positioned and joined to the upper and lower shell. These four shell elements and a floor grid form a section. To fulfill tolerance requirements the biggest components of a section, the left and the right side shells, have to be positioned and untwisted. The untwisting is needed to compensate the deformation of the shell (mainly due to gravity). A robotic system has been developed for this process [6] and is already used in industry. 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 have its correct shape yet, the actuators can not meet the desired grasping point exactly and also the position of measuring points are only estimations. In an iterative process the deviations between target and desired position can be determined and the residual can be minimized [6]. The control of the station is done automatically, as long as force limits are not exceeded. In that case a worker has to continue the process manually, as data from force/torque sensors is not considered for the automatic control.

The principles of this semi-automatic process in section assembly are being used and enhanced for the control of an automated shell assembly using self-optimization in a robotic production system.
3. Concept of self-optimizing shell assembly

A systematic approach to set up the desired assembly systems starts with an analysis and description of the products/parts, continues with the definition of assembly processes (see chapter 2) and finally ends with the design of assembly equipment.

The use of a robotic system instead of fixed jigs facilitates not only an increased flexibility of this process but also the opportunity for a complete re-design of the assembly sequence. As the assembly is done only in a local area of the panel, also the untwisting and shaping of the panel can be done by robots in a local area. The assembly of clips can even be done at a deformed panel, as the desired position of each clip can be determined related to that deformation. After the panel has been untwisted, also the clips will have the desired position and orientation. As the panel has to be supported at several points during handling, a large number of grasping points is required. In order to achieve a maximum of flexibility and not to limit the handling system for a special geometry of the product, only one or few grasping points are provided for each actuator. This results in a large number of actuators which handle the product in a cooperative layout. Therefore, the payload and number of active joints for each actuator can be reduced which leads to light-weight, cost-efficient handling modules [7] for large components. After the panel is untwisted and the clips are joined, frames are assembled to secure the final shape of the panel. The positioning and joining of clips and frames can be done by a standard industrial robot with 6 DOF (figure 3).

4. Models for self-optimizing process control

For an automated control of the untwisting process, models and control algorithms are required which generate robot motions based on the components behavior and process states (geometrical deviations, forces, ...). As the reaction to external forces is different for each product and can not be planned in advance, not only automated but self-optimizing solutions are being explored for the automated untwisting of large components during shell assembly. The required model of the product, its interdependencies to the process and the assembly equipment (robots, grippers, sensors,...) is in focus of this chapter.

The description of the positioning and untwisting process has already been investigated for the assembly of aircraft sections [6]. It is based on geometrical transformations between the product, actuators, grasping points etc. and their deviations. One important aspect which is not yet included in the algorithms are forces. Sensors at the actuators detect forces, but the correlation between a motion of an actuator and the force flow within the product is widely unknown and restricts a completely automated control of the assembly process. If a warning threshold of a force/torque sensor is reached, the machine switches off and the motions of the actuators have to be continued manually, always monitoring the data from force sensors in order not to exceed the force limits of the panel.

To build up a model which also includes forces, theories of mechanical engineering have been researched, which define the panel as a “thin-walled, generally curved bodies” [8]. In contrast to plane stress components, which can only transfer forces within body layer, and in contrast to membranes, which can only transfer forces orthogonal to its surface, panels/shells can transfer forces in all
directions. Modeling and calculating these elements is very complex [8], especially for real components, which have no uniform structure but additional stiffening elements, holes for windows, material deviations etc. On the one hand algorithms have to calculate accurate results, on the other hand these results have to be generated online during assembly, in order to meet requirements of industrial production. Therefore, a compromise between accuracy and efficiency in the algorithms has to be found. The approach is to describe the real physical behavior with approximate functions in order to reduce mathematical formulations as far as possible and to use additional sensor data for process control.

For the mathematical description the panel is approximated by a matrix of small stiff plates which are connected by springs and dampers and describe the local stiffness and global compliance of the panel (see figure 4). This characteristic is the reason why the panel can be grasped and moved by several robots in a cooperative layout, each gripping at one plate.

![Modeling of product, process and kinematics for self-optimizing process control](image)

The basic relation between a force ‘F’ resulting from a motion (along distance ‘x’) against a plate with a stiffness ‘c’ (in direction of the force) can be calculated by

\[ F = c \cdot x \]  

(1)

Depending on the direction of the motion, a tensile or a compressive force is applied. The force and the distance can be measured by a force/torque sensor and a measurement system. The desired model of the product is represented by the stiffness between the plates, which has to be estimated from experiments.

For the experiments a training procedure has to be executed after a panel is fed to the assembly station and before the untwisting process can be done. During this training procedure one actuator pushes against the panel with a predefined force and the resulting deformation at all plates is measured. This procedure is repeated for all relevant plates/areas of the panel. Subsequently, the correlation between a force and the deformation can be calculated. As two input variables (force and deformation) are used to calculate one output variable (stiffness) and as the correlations are assumed to be linear (for small motions and in a local area), a multiple linear regression is used to build up the model of the product [9],[10]. The selected linear regression model is

\[ x_i = \beta_0 + \beta_1 F_{i,1} + \beta_2 F_{i,2} + \ldots + \beta_n F_{i,n} + \epsilon_i \]  

(2)

or written as a matrix

\[
\begin{bmatrix}
  x_1 \\
  x_2 \\
  \vdots \\
  x_n
\end{bmatrix} = 
\begin{bmatrix}
  1 & F_{1,1} & \ldots & F_{1,n} \\
  1 & F_{2,1} & \ldots & F_{2,n} \\
  \vdots & \vdots & \ddots & \vdots \\
  1 & F_{n,1} & \ldots & F_{n,n}
\end{bmatrix} 
\begin{bmatrix}
  \beta_0 \\
  \beta_1 \\
  \vdots \\
  \beta_n
\end{bmatrix} + 
\begin{bmatrix}
  \epsilon_1 \\
  \epsilon_2 \\
  \vdots \\
  \epsilon_n
\end{bmatrix}
\]  

(3)
Defining

\[
\begin{pmatrix}
    x_1 \\
    x_2 \\
    \vdots \\
    x_n
\end{pmatrix} =
\begin{pmatrix}
    F_{1,1} & \ldots & F_{1,k} \\
    F_{2,1} & \ldots & F_{2,k} \\
    \vdots & \ddots & \vdots \\
    F_{n,1} & \ldots & F_{n,k}
\end{pmatrix}
\begin{pmatrix}
    \beta_0 \\
    \beta_1 \\
    \vdots \\
    \beta_n
\end{pmatrix} +
\begin{pmatrix}
    \varepsilon_1 \\
    \varepsilon_2 \\
    \vdots \\
    \varepsilon_n
\end{pmatrix}
\]  

(4)

simplifies equation 3 to

\[
x = F \cdot \beta + \varepsilon
\]  

(5)

The coefficients ‘\( \beta \)’ represent the reciprocal of stiffness ‘\( c \)’, i.e. the compliance, and can be calculated by

\[
\beta = (F^T \cdot F)^{-1} \cdot F^T \cdot x
\]  

(6)

The variable ‘\( \varepsilon \)’ represents the error between the linear regression model and the experimental data and can be calculated by

\[
\varepsilon = x - F \cdot \beta
\]  

(7)

Index ‘\( i \)’ in equation 4 represents the data of one single experiment, ‘\( n \)’ is the total number of samples for one plate (i.e. \( 1 \leq i \leq n \)), ‘\( k \)’ is the number of plates/ positions where a force is applied or measured.

One critical aspect of this linear regression are interdependencies between the input data, as a force of one actuator also effects another actuator. These interdependencies can lead to a numerical instability or invalidity of the model. As the model is build up and used only in a local area of the panel (where a frame has to be assembled), the interdependencies can be neglected, but this has to be checked in ongoing experiments. In case of significant interdependencies a more complex approach has to be used to model the products behavior, e.g. knowledge based control principles or neural networks.

After the training procedure has been finished, the model can be used for process control. For the execution of the untwisting process each actuator is controlled by forces, not by position. This guarantees that force limits are not exceeded during assembly. With the known (local) stiffness of the product the required forces can be calculated to achieve the desired contour of the panel. The modeling and force control of the actuators, which are also an important part of the process, is mainly state of the art [11] and needs no description in this article.

5. Robot system for shell assembly

The depicted process of shell assembly is being validated at a robot test stand. The cell consists of a downsized CFRP panel (stringers already integrated) with dimensions of 1.7m x 2.1m (temporarily hanging in an aluminum frame), two industrial robots (Kuka KR 60 and Reis RV130) with grippers/ tools, cameras as local measurement systems and Nikon iGPS for global referencing (figure 5). The Kuka robot is equipped with a vacuum gripper to grasp the panel and to locally correct its shape. Within the next years the system will be extended with special actuators/ kinematics (see figure 3), which will replace the aluminum frame and can flexibly handle the panel, adjust its position during assembly and increase the flexibility of the overall system.

![Figure 5. Validation set-up for self-optimizing assembly of aircraft shells](image)
6. Conclusions

Robot-based assembly systems in combination with measurement systems can replace fixed jigs and increase flexibility of a production system. In aircraft production some processes have already been examined and implemented with robotic systems. The depicted project concentrates on the self-optimizing automation of shell assembly by using robots. 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 control without manual intervention by workers. For this automated control models are required, which describe correlations between product, process and equipment. Multiple linear regression has been presented as an approach to build up a model for the untwisting of an aircraft panel that has no intrinsic rigidity. After the panel is fed to the assembly station, the correlation between forces and deformation is determined in short experiments and a multiple linear regression is used to calculate the local stiffness of the panel, which approximates its physical model for the considered workspace. During assembly of frames, deformations of the panel can be compensated by force control of actuators and the desired shape of the product can be adjusted in the relevant area of the panel. The depicted approach of product and process modeling for large components is being validated on a demonstrator. In future work the models can be enhanced based on experimental results and adjusted for the assembly of different aircraft panels. The model of the product is the basis to develop motion strategies for actuators which allow an automated untwisting of deformed large components in shell assembly.

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8. References


