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Automated Production of Large Fibre Metal Laminate Aircraft Structure Parts

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Abstract

Fibre metal laminate (FML, GLARE©) materials, consisting of alternating layers of thin aluminium sheets and glass fibre prepregs, can be used for aircraft structure parts. For optimal structural properties and weight, large aluminium sheet sizes are desirable, making manual handling of the parts difficult. This paper introduces a software toolchain for the automated production of an aircraft body part using cooperating industrial robots. Multiple robots are required due to aluminium sheet of lengths up to 5800 mm and widths up to 1000 mm. No manual robot programming is required; all robot control programs are automatically created from CAD files and can be previewed in a 3D simulation environment. A full-scale demonstrator has been built using this toolchain.

Keywords: manufacturing; robotics; simulation; GLARE

1. Introduction

For more than 20 years Fibre Metal Laminates (FML) have been in the focus of aircraft industry due to their excellent material properties (see e.g. [4, 13] for the beginnings and an historical overview of this technology, and e.g. [2, 5, 14] for the material properties). Here we focus on the manufacturing of large parts of GLARE (Glass

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Laminate Aluminium Reinforced Epoxy) which consists of alternating layers of aluminium sheets and glass fibre. In this paper in particular we concentrate on the process chain of the laying process of the aluminium parts which have dimensions of roughly 5800 mm × 900 mm) and of 2000 mm × 1000 mm. Moreover, two splice straps of 5700 mm × 60 mm are to be handled. For an automated production these dimensions require the use of two cooperating robots which place the sheets into a mould.

Recent research concerning the manufacturing of FML parts deals with the utilized materials [16]. [9] addresses particularly the resin, and also sheds light on subsequent production steps as water jet and laser cutting . In [10], the forming of GLARE is addressed. In [12], lay-up techniques are discussed but without any efforts to automatize the process. In this paper we report on the automated laying of large aluminium sheets in the context of manufacturing a GLARE fuselage demonstrator at the German Aerospace Center (DLR) in Augsburg. The large size of thin aluminium sheets makes manual production difficult, and also automated production of FML parts is attractive to satisfy high quality requirements. In aircraft industry the overall number of produced planes is rather low (in particular compared to the heavily automated automotive industry), but the number of different parts is high. Therefore, an automation solution should not depend on manual generation of robot programs by moving robots and adjusting their motions in the real-world execution environment by hand (often referred to as *online programming* or *teaching*). Instead all motions were planned and programmed offline which of course presupposes an exact measurement of the process environment. To handle the large sized aluminium sheets cooperating robots with special grippers suitable for the manipulation of metal sheets are used. Extensive simulation is necessary to identify potential problems during the manufacturing process such as collisions of the robots with the mould, or of the robots among themselves. The demonstrator has been built using the multi-functional robot cell [6] at DLR Augsburg. This cell consists of 6 robots in total, thereof three KUKA KR-270 R2700 hanging from a common linear unit on a gantry. This layout allows optimal accessibility for a plane pick-up table (for preparation of aluminium sheets) and the concave double curved mould.

The plybook is based on the real geometry of an Airbus A320 aircraft rear panel and was specifically developed for the demonstrator. It covers both single- and double curved areas and contains unique design features for FML panels that were implemented to validate the feasibility of the examined automated process chain. Novelties include the use of splice straps to stiffen long splices, the size of single aluminium plies and a so called T-splice in the double curved area of the mould, where the design changes from longitudinal to circumferential aluminium sheets. In total the plybook consists of 15 aluminium plies, nine longitudinal sheets, two splice straps and four circumferential sheets. The largest plies are the longitudinal sheets which are up to 5800 mm long and 900 mm wide while the circumferential sheets are roughly 2000 mm long and 1000 mm wide. The splice straps are long slim sheets with a length of 5700 mm and a width of 60 mm. These sizes were chosen based on the curvature of the respective area of the mould in order to prevent buckling of the flat sheets when vacuum is applied. The layer structure consists of three layers of aluminium stacked with two layers of glass fibres where longitudinal sheets are placed and two layers of aluminium stacked with one layer of glass fibres on the other side of the T-splice. We describe the considerations leading to the gripper construction in section 2. Subsequently, we explain the construction of the grip and drop points in section 3.1, followed by a description of the robot program generation in section 3.2. Finally, we sum up and discuss our results and give an outlook to further work in section 4.

2. Gripper Construction

A key requirement for the grippers is their ability to transport and transform plane aluminium sheets into the double curved mould. One curvature can be achieved by the position of both grippers relative to each other; the other curvature must be done by forming each gripper itself. Because each sheet requires slightly differently curved grippers, the adjustment must be automated. A picture of the end-effector during the adjustment process for a new curvature is displayed in figure 1. In contrast to earlier versions of the gripper [3], the stiffness has also been increased.

The design is a kinematic chain of nine modules with a width of 176:5 mm each, one module fixed in the centre and four adjustable modules on each side. The total length on which plies can be gripped is 1506 mm. The elements have one degree of freedom around the circumferential axis and can be tilted between 0◦ and 15◦ relative to the previous element. As a consequence the gripper can adapt its curvature to radii of up to 1304 mm. Each element is driven by a linear actor and can be adjusted independently. The outermost elements are reinforced against the robot flange with a brace of variable length if a pneumatic brake is opened. This way the stiffness is improved and the endeffector keeps its shape despite the occurring forces caused by the handling process. The aluminium sheet is gripped using suction cups and a vacuum pump. Each module can be activated and deactivated separately.

Figure 1: One of the grippers with one arm fully curved (left) and one arm straightened (right)

The curvature adjustment of the gripper is performed with no aluminium sheet attached to the gripper. This allows for an easier mechanical construction without the risk of shearing the aluminium sheets. To pick up a sheet a rolling motion has to be performed with attaches the modules one by one and therefore transforms the sheet during pick-up.

3. Offline Programming

To provide a completely automated process chain from CAD to the shop floor two steps are required: first, the grip- and drop-positions of the grippers are calculated, and subsequently robot programs (including gripper control commands) that perform all necessary motions are generated.

3.1. Grip- and Drop-Point Generation

For the generation of the grip- and droppoints we used a custom tool which allows the positioning of the gripper on the flat grip positions and therefrom calculates the drop positions in the mould and the distortion of the gripper. One of its main inputs is a so-called mesh, exported from the CATIA CAD model by a CAT VBA script. It contains pairs of points where the first point lies on the flattened sheet and the second one is the corresponding point on the sheet in its position in the mould. A position of a module of the gripper on the two-dimensional flattened sheet is represented as a local two-dimensional Cartesian coordinate system, i.e., by one 2D point as origin and two 2D points indicating the direction of the local x- and y-axis. Using the mesh these three points are used to compute a local coordinate system in 3D in the mould which determines the 6D pose of the gripper module under consideration.

This tool is a further development of the tool introduced in [11]. In contrast to there we have to handle two grippers and face the challenge of actively formable grippers due to the part's dimensions. The gripper from [11] is not actively formable but adapts to the mould by passive slight deformation. In the present case we form the gripper actively (see also section 2) which has to take place also on the offline programming. To this purpose, an STL file of the mould was exported from the CAD model and used to compute the angles of the joints of the modules. In order to obtain an optimal solution we first positioned the middle module directly on the mould. Subsequently, we computed the angles between the modules iteratively starting from the middle proceeding in the outward direction while keeping the previously processed modules at their already computed positions. Every angle was chosen in a way which sets the distance between the module's midpoint and the mould's surface to zero. Modules which are not part of the gripping process are flapped up in order to avoid potential collisions with the mould.

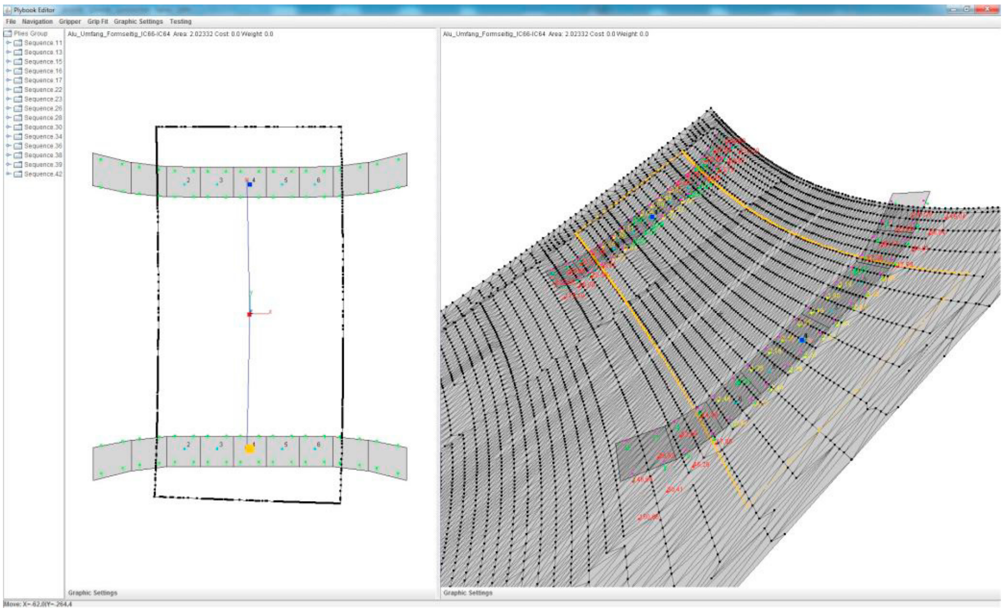


Figure 2: A Screenshot from the Offline Programming System for Gripper Positioning

Figure 2 shows a screenshot from this tool. On the left-most part the user can choose the sheet to edit. In the middle the flattened sheet together with the already deformed grippers is shown. Finally, the right part shows the mould together with the grippers and the sheet indicated by its contour by a yellow line. Both parts also show the flapping up of modules not taking part in the gripping process.

At this point, only the start and end positions of the grippers (at their respective grip and drop positions) are calculated. This information is stored in an XML-file which is forwarded to the offline program generation. This tool is described in the following subsection.

3.2. Offline Program Generation

For path-planning and robot program generation, an offline programming environment has been developed which is based on an earlier system that was created for the AZIMUT project[8]. In this project, a single robot had to handle dry fibre textiles for the automated production of carbon-fibre reinforced plastics (CFRP). While several components could be reused (e.g. the plybooks for CFRP and GLARE materials share many features), a key requirement for handling the large aluminium sheets was the use of two cooperating robots. The Eclipse integrated development platform has been used as base for the offline programming environment. Figure 3 shows a screenshot of the tool. In the left-most column, different projects can be managed (similar to "standard" Eclipse projects), while in the middle column, the sequence of robot tasks for the selected plybook can be seen. Each task can be generated and simulated separately. In the right column, the 3D simulation is displayed. Selecting a task in the middle column automatically updates the simulation view to the start position of the selected task, and double clicking a task starts the simulation. The offline programming environment uses the Robotics API[1] and the Robot Control Core[15] (both developed at Augsburg University) for the simulation of robot motions.

Since the position of the grippers on the aluminium sheets are already defined during grip- and drop-point generation (cf. section 3.1) and the position of the sheet in the mould is defined in the plybook, the layup motions can be generated automatically. For picking up the sheets from the table however, only the position of the grippers relative to the sheets are known, but not the position of the sheets relative to the environment. Therefore, a manual step has been included which requests the user to perform a graphical specification of the position of the sheet on the pickup table. For precise positioning, the corners of the sheet can be aligned with edges of the table both in simulation and in reality (using stop angles).

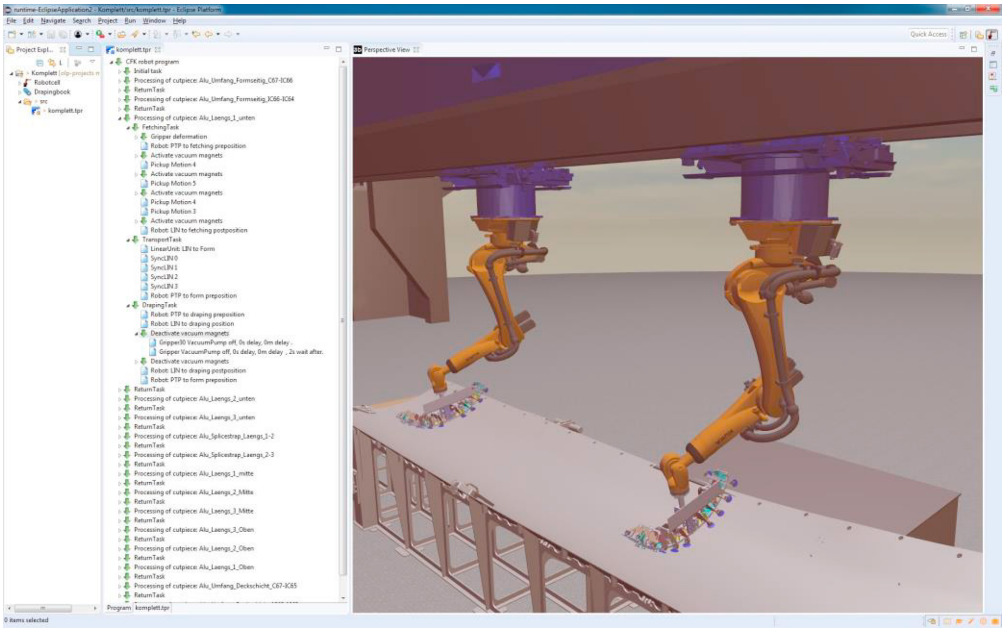
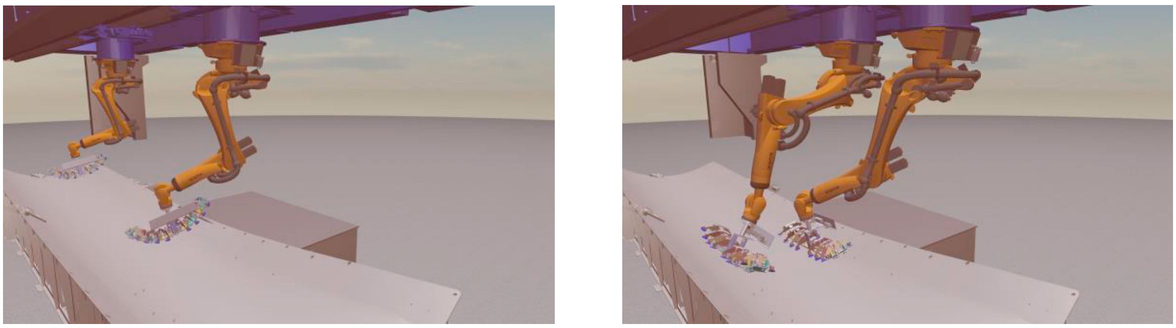


Figure 3: Offline programming tool



(a) Same configuration for longitudinal sheets

(b) Different configuration for circumferential sheets

Figure 4: Different configurations (status/turn) of both robots are required depending on size and position of aluminium sheets. Screenshot of the 3D simulation environment.

Now that all required position data is available, the offline programming environment can plan the motions for both robots. The program for each aluminium sheet consists of the following steps:

1. The robot configuration is prepared for the next sheet
2. The angles between gripper modules are set as required
3. The sheet is picked up simultaneously with both grippers
4. The sheet is transferred from the pickup table to the mould
5. The sheet is dropped into the mould appropriately
6. The robots are returned to the pick-up table

Due to the widely different sizes of aluminium sheets it is necessary to use different configurations (known as *status* and *turn* for KUKA robots) of the involved robots to avoid collisions of the robots or the grippers. For large longitudinal sheets, both robots can be used in the same configuration (cf. figure 4a), while for smaller circumferential sheets different configurations are necessary (one robot "elbow up", the other robot "elbow down", cf. figure 4b). Due to the very limited workspace, using different robot configurations for all sheets is not possible. If a configuration change is detected for a robot between the last and next sheet, specific robot commands are created which use point-to-point (PTP) motions in combination with joint angles to guarantee for a specific configuration.

The angles between the modules of the gripper are determined during the grip- and drop-point generation phase. These values are used for several purposes: visual representation in the 3D simulation environment, dynamic calculation of tool centre points (TCP) of the grippers during the pickup motions and for creating control commands in the robot program that allow automated adaption of the grippers for each sheet. The aluminium sheets are prepared as plane objects on the pickup table and need to be transformed into a curved (possibly double curved) shape in the mould. Depending on the direction of the main curvature, the deformation can either be created by a defined angle between both grippers or by angles between the single modules of the grippers. If there is an angle between two adjacent gripper modules, the modules have to pick up the sheet sequentially, therefore creating a "rolling" pickup motion. The XML file provided by the grip- and drop-point generation includes coordinates for each module on the plane aluminium sheet. The roll-up motion is created by dynamically defining the TCP of the robot at the centre of a module (including the chain of angles between other modules) and moving the newly defined TCP to the planned coordinates. Once the gripper has reached the final position, a signal to switch on the appropriate vacuum valve is generated. Since the aluminium sheets are almost rectangular, the same number of modules are active on both grippers, and pick up can be synchronized between both grippers.

Once the first gripper module makes contact with the sheet, a strict synchronisation of robot motions is required. The KUKA KRC-4 controller provides an optional technology package called "KUKA.RoboTeam" for motion synchronisation of multiple robots. Three synchronisation modes are possible:

1. Program synchronisation: The starts of all motions are synchronised, but not the duration.
2. Motion synchronisation: Start, duration and the individual phases (acceleration, deceleration, etc.) of the motions are synchronised. This type of synchronisation is only possible for continuous path motions (linear, circular or spline), but not for point-to-point motions.
3. Geometrically linked motions: One or more "slave" robots are geometrically linked to a "master" robot and follow every motion, maintaining the exact position of their TCPs relative to the master's TCP. Only the motion of the master must be programmed. This type of motion synchronisation does not allow external joints (like linear units) to be used.

For the transfer motion between the pick-up table and the mould, motion synchronisation is used. Program synchronisation is not sufficient, and geometrically linking the robots is not flexible enough, besides the requirement for the usage of the linear unit. To guarantee a synchronous movement with no undesired relative motion of the grippers, the TCP of each robot is set to a common point near the centre of the aluminium sheet. Since each robot controller plans for the same virtual point, the resulting path does not contain any relative motions of the grippers. Special care has to be taken in the specification of maximum velocities for the virtual TCPs (which can be far away from the robot flanges) in particular for rotations in order not to exceed the allowed speeds of the robots.

The Cartesian coordinates for grip- and drop-points do not include any information about the linear unit position of the robots. In fact, the 7th joint adds redundancy to the system, i.e. there is no finite number of possible solutions to reach a certain grip- or drop-point. The linear unit position therefore is calculated by projecting the grip-/drop-point to the linear unit and adding an offset. The offset has been determined experimentally and is necessary for optimal use of the workspace available to the robots. The joint positions calculated by this scheme then are validated and slightly adjusted if both robots are too close. Repositioning the linear unit during the transfer motion does not affect the motion of the TCP, the required kinematics calculations are done by the KUKA controller. Therefore, there is no need for additional synchronisation of the linear units besides the prevention of collisions.

After the aluminium sheet has been transferred from the pick-up table to a position above the desired position in the mould, the grippers are geometrically uncoupled. Due to the tack of the glass fibre prepregs, the aluminium sheets must make contact with the mould at the lowest point first and then be “draped” to the final drop points without creating wrinkles. This is achieved by placing the aluminium sheet directly above the mould with both grippers positioned slightly inwards (the mould is concave), lowering the sheet until contact at the bottom is made and finally moving the grippers outwards onto the drop-points.

The last step is the retraction motion of the robots to the start position for the next sheet. Since the transfer trajectory into the mould has proved to be collision-free, the same path is used for retraction, although no geometrical coupling of the robots would be necessary. This step provides some potential of optimisation of the cycle time if required. Optimal cycle times however were out-of-scope for the current project.

The offline programming environment uses the Robotics API for the simulation of all robot and gripper motions. Internally, the paths are stored as list of intermediate coordinate points, enriched with meta-data about required synchronisation, gripper controls or robot configurations. For execution on the real robot hardware, the internal data representation must be translated into the KUKA robot programming language KRL. In most cases, linear motions (LIN) are used in combination with Cartesian coordinates. Depending on the position of the target, the base coordinate system is dynamically chosen between one base coordinate system at the pick-up table and two base coordinate systems in the mould. Point-to-point (PTP) motion commands are only used if no aluminium sheet is attached to the grippers, and either control of the joint angles (for configuration selection) or faster motions are required. In KRL, motion synchronisation is achieved by adding a specific synchronisation command right in front of a motion command, which is done automatically every time the meta-data requires so.

For each aluminium sheet, a separate KRL program is generated. This allows to integrate the aluminium pick- and place-process into the overall process control, e.g. a programmable logic controller which also has to other process steps such as the laying of glass-fibre prepregs.

4. Conclusion and Outlook

Using the software described in section 3 and the hardware described in section 2, it was possible to place all aluminium sheets for the fuselage demonstrator without teaching a single robot motion manually. Only the base coordinate systems in the mould and on the pick-up tables had to be defined manually by moving the robots to appropriate positions. This greatly increases the absolute positioning precision of the robots which otherwise would completely depend on the precision of the robot gantry construction and the location of the mould. A video of the automated lay-up process is available[1]. Using simulation technology greatly reduced the time required on the shop floor and in general lead to a smooth start-up.

Although almost no manual steps on the shop-floor level have been necessary, during the offline-programming process there is still a lot of human expert knowledge required. The positioning of the grippers on the sheets is done manually by experience, and also the path planning from the pick-up table to the mould has been optimised by human experience. For the automated production of carbon-fibre reinforced plastics, the multi-robot collision free path-planner *KOKO* has been developed[7]. In a next step, this system could be adapted to the domain of metal sheet handling and thus also automate the whole transfer motion for arbitrarily shaped aluminium sheets.

The long-term goal is the complete automation of the process, i.e. only a CAD file containing the plybook of the part and a model of the process environment should be necessary. Executable robot programs, control commands for the grippers, etc. should then be generated automatically without the need for any interaction.

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[1] Video of lay-up (starting at 3:55): https://youtu.be/_apnebyIKIM?t=235

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