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Autonomous Manufacturing of Composite Parts by a Multi-Robot System

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Abstract

This work considers an autonomous multi-robot pick-and-place process for the manufacturing of aerospace structures, which consists of the steps picking, transfer, dropping and post-drop treatment. Autonomous production is achieved by combining computer vision assisted gripping, automated transfer path generation and generic process execution in one system. Test scenario is an airplane skin demonstrator made of tailored carbon fiber multiaxial fabrics that are placed in a half-shell shaped jig of approximately 4 m in diameter by two cooperating robots mounted on a common linear axis.

Keywords: Multi-Robot system, Autonomous manufacturing, task oriented programming, computer vision, composites, generic description

1. Introduction

Aerospace structures require a combination of low weight and high mechanical performance and thus often involve composite materials, e. g. carbon fiber reinforced plastics (CFRP) or fiber metal laminates (FML). The laminate structure involves complex layups of hundreds of cut-pieces, which makes manual production demanding or even error prone. Today, there still is a lack of innovative production techniques to achieve competitive production rates, especially for parts that are produced in a vacuum assisted process. The amount of cut-pieces and

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the variability of parts make the use of industrial robots for production a challenging option, because the teaching efforts are vast and sometimes would even exceed the production time. Automating this processes demands a smart and flexible, however robust system directly linked to the CAx (computer aided technologies)-process chain that eliminates teaching. Commercial products like Delmia or Process Simulate are one step in the right direction, but more useful for digital factory planning. Add-ons for offline-programming like Cenit's Fast Suite extend the functionality towards digital production, but lack the ability of handling huge numbers of cut-pieces. Further shortcomings are in the field of sensor integration and in multi-robot processes. This is where autonomous manufacturing systems for multi-robot applications come to turn.

2. Experimental Setup: Production Scenario for large Composite Aerospace Structures

Fiber-placement and tape-laying are established technologies for the production of CFRP aerospace structures. Broadly speaking, fibers or narrow CF-tapes, dry or pre-impregnated with thermoset or thermoplastic resin, are laid down to a jig by dedicated rollers. The technique is highly productive thus extremely specialized to a limited scope of material combinations and geometries. Another, yet not so well-established approach is preforming with a robotic pick-and-place process [1], which consists of the steps picking, transfer, dropping and post-drop treatment. The process can be applied to a wide variety of materials and also covers the integration of inserts or subparts. However, the process lacks specificity, which is an obstacle for automation as long as the automation strategy stays unclear. Basically, being specific seems to conflict with generic solutions. So we considered a concrete application scenario - the production of an airplane skin demonstrator made of dry CFRP sheets (Fig. 1) - and searched for a process that allowed staying as generic as possible.

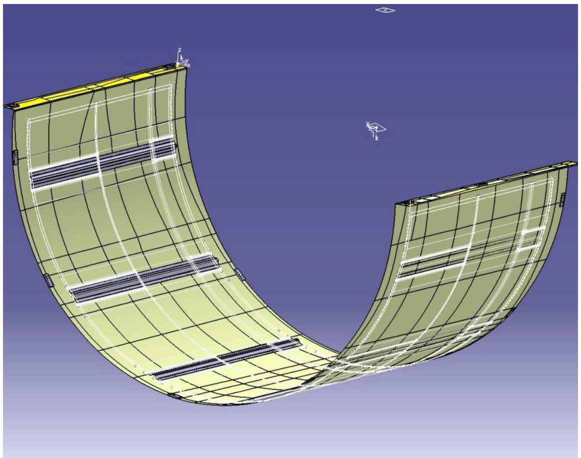

Fig. 1.Use-case for automated CFRP fuselage production: Panel demonstrator.

In our scenario we use two cooperating robots of the type KUKA Quantec KR210 R3100 on a common linear axis of 8 m length to cooperatively grip, transfer and drop the cut-pieces. The jig for placing the cut-pieces is half-shell shaped with a diameter of approx. 4 m and a length of approx. 2 m, while the 108 cut-pieces are approx. 1.2 m by 1.8 m and approx. 1.2 m by 0.8 m in size and are provided in a drawer based storage system. The robot cell with storage system, robots on linear axis and jig is shown in Fig. 2. Two robots grip the cut-pieces, transfer them cooperatively to the jig and drop them to the desired CAD-position. Both robots are equipped with nine-zone high volume flow vacuum-grippers suitable for permeable goods and can tack the materials in order to prevent them from later slipping. Robot 1 (left) is also equipped with a computer-vision system for cut-piece detection (Fig. 3).

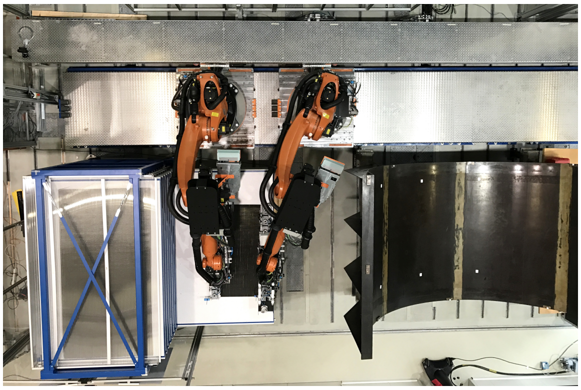

Fig. 2. Production cell for CFRP-Skin (view from above).

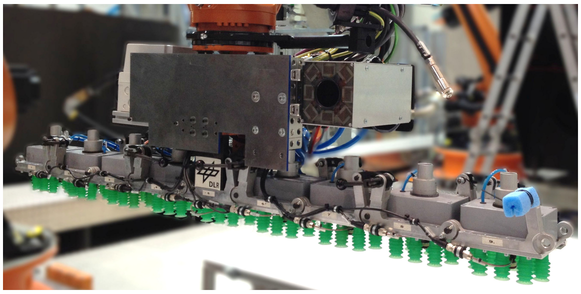

Fig.3. Robot 1 vacum gripper with computer vision system.

3. Generic Process description: General and Specific Requirements for Pick and Place

A generic description of pick-and-place is relatively easy: pick from point A, transfer, lay down to point B. A close look at the coordinates A, B reveals several facts: The robot's orientations have to be considered, thus we have to speak of 6D-coordinates, commonly represented as frames (x,y,z,a,b,c) with x,y,z being the Cartesian coordinates and a,b,c the Euler angles. For reasons of robot accuracy frame A is denoted in the coordinate system of the cut-piece supply, referred as grip-base, while frame B refers to the jigs coordinate system, subsequently called drop-base (Fig. 4). For every robot the bases differ slightly due to imperfections in robot installation. Once the cut-piece is gripped the transfer has to take place either in the common WORLD coordinate system or in an intermediate transfer base. Since grip-point A and drop-point B are within different coordinate systems, before transfer they have to be transformed into one common coordinate system, e. g. the robots WORLD.

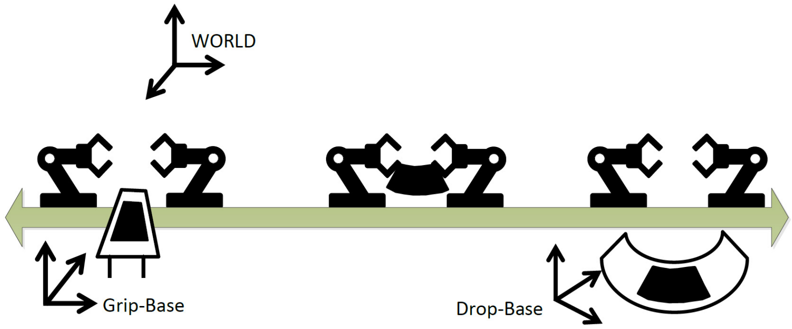

Fig. 4. Minimum set of applicable coordinate systems during grip, transfer and drop (from left to right).

To simplify the transformation handling the frames are converted to homogenous coordinates which have matrix-properties and can be multiplied for concatenation or inverted for the inverse transformation. Defining G as the grip-base and D as the drop-base, grip-point A and drop-point B may be obtained in the WORLD coordinate system by $A_{WORLD}=G*A$ and $B_{WORLD}=D*B$ and transfer can take place in the WORLD-frame. If a transfer-base T is needed for the transfer the desired coordinates are given by $A_{Transfer}=T^{-1}*A_{WORLD}=T^{-1}*G*A$.

To be as generic as possible only the grip- and drop-points for every cut-piece and every robot together with some meta-information about robot-TCP, which vacuum-grippers to use and which welder to activate for welding as well as the cut-piece contour, which is necessary for the camera detection, are provided in a proprietary, human-readable job definition file format (jdf) [2]. While XML or the later implementation in a network service is an option we decided to choose the way of human-readability and human-interaction with the job definition for R&D-purposes, where quick and easy changeability in the field is extremely helpful. Also provided is a model of the robot cell plus drawer storage and jig that allows the system to find a collision free path from drawer to jig for every cut-piece.

4. System Layout: Autonomous Manufacturing System for Multi-Robot applications

It was shown in previous work that a robot's target points for gripping and dropping cut-pieces can be derived automatically and subsequently the layup can be carried out autonomously (e. g. [2, 3]). Furthermore was demonstrated that computer vision strongly improves process accuracy and robustness (e. g. [2, 3]). The focus of this paper lies on the practical implementation of a smart manufacturing execution system (MES) in a multi-robot environment. Major components of the cyber-physical system are:

- The manufacturing execution system plus cut detection interface (CDI)
- The robots and their controllers
- One ore multiple computer vison systems for detection of the goods being handled, and
- A simulation environment called CoCo for collision avoidance (e. g. [4]).

The investigated system architecture is shown in Fig. 5:

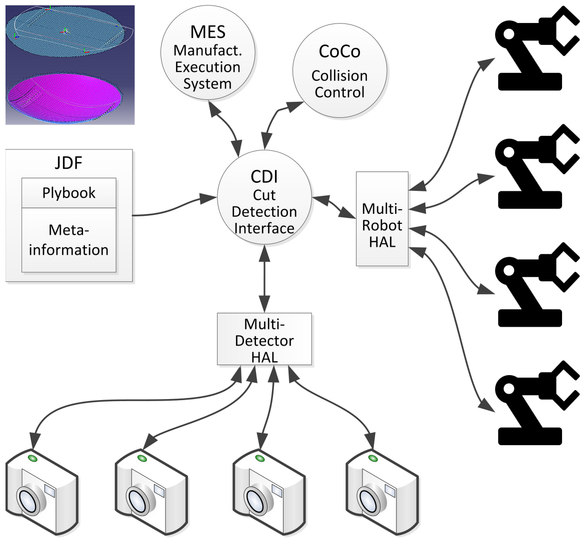

Fig. 5. System architecture.

Another key area is the integration of the different systems that have already shown their capabilities separately into one autonomous cyber-physical system and to study promising ways for improved system architecture. The generic layup-information, provided in the jdf-file is fed to the Cut Detection Interface and MES. A parser converts the generic jdf-information to an action list for each robot comprising setting the tool center point, move the robot, switch the grippers and do the post-drop tacking. Today there is no strict separation between the two systems since separation means interface design and interfaces in R&D change often. Again, there is the option for later implementation as network-services to enhance flexibility. The CDI is capable of handling several detectors that can be mounted to the robots or fixed to the cell. Between the CDI and the detectors a hardware abstraction layer (HAL) ensures the triggering of the right cameras, the coordinate transformations between cameras and robots, and, if applicable, the fusion of the results of multiple detectors looking at the same cut-piece. One important point is that it has to be distinguished if a camera is physically mounted to a robot or if the relation is only logical. This makes a difference as soon as there is no 1:1 correspondence. For example every camera has to be triggered only once. If it is robot-mounted a corresponding robot motion may be required before triggering. Fig. 6 shows a theoretical example of what is possible.

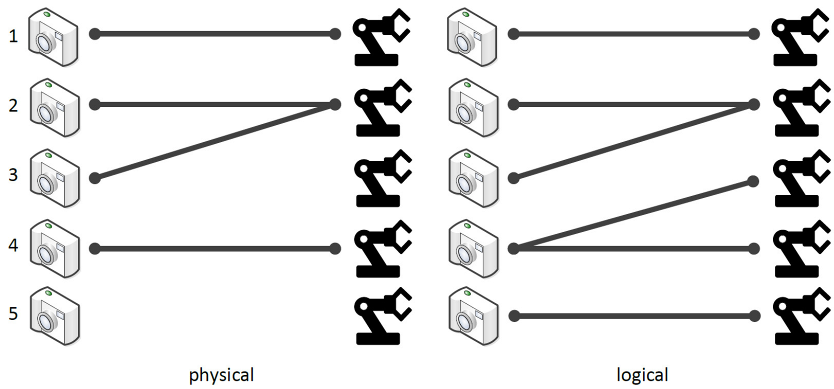

Fig. 6. Detector HAL: multiple cameras for multiple robots.

In this example camera 1 is physically and logically connected to robot 1. Cameras 2 and 3 are both mounted to robot 2 and are only responsible for robot 2, thus the results have to be fused to give robot 2 one single grip-point. Camera 4 is mounted to robot 4 but transmits detection results to robots 3 and 4. Here, the detector results have to be split and transformed into the coordinate systems of robot 3 and 4. Camera 5 is not mounted to a robot but delivers coordinates for robot 5. Our real test scenario was comparably simple with one camera mounted to the first of two robots, supplying both robots with cut-piece coordinates in the respective coordinate systems.

On the robot-side another HAL is needed, since the robots are remote-controlled and the peripheral equipment is connected to the robots by a fieldbus. The robots pass-through the CDI commands to the bus components (Fig. 7). For interfacing to the robots a small KRL(KUKA Robot Language)-program is running that receives the necessary actions by the KUKA technology package “Ethernet KRL”. Since this has nothing to do with real time, time critical motions like cooperatively transferring a cut-piece are first transmitted, locally stored in a table and then executed synchronously by use of the KUKA technology package “RoboTeam” using the PROGSYNC and MOTIONSYNC commands. A use of GEOLINK turned out to be unnecessary since the geometric relation between the grippers is maintained by the CoCo path planner. Although the system is well aware of how to correctly grip, drop and weld the cut-pieces it is not aware of how to safely transfer the cut-pieces from one side of the cell to the other. This is where the CoCo planner’s results are requested and subsequently handled as described just above after the necessary robot setup has been performed in non-realtime.

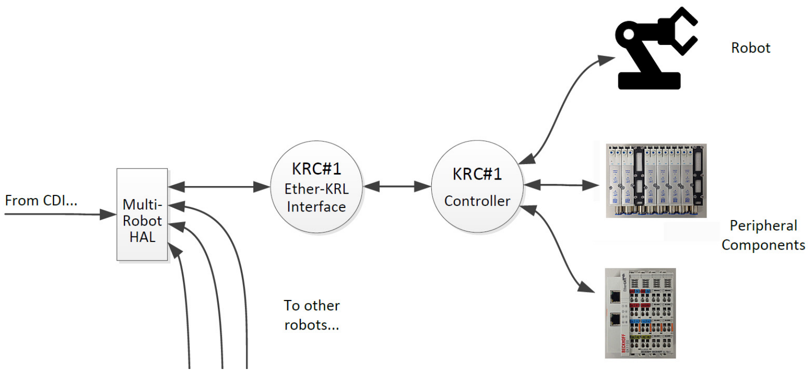

Fig. 7. Robot HAL: network-based abstraction of robot and peripheral devices.

5. Experimental Results

After completing the programming work the system was tested. Extensive loops of testing, debugging and retesting were performed until the stability was sufficient. After all we tested approximately 250 detections, 35 cooperative grips, 73 transfer renderings (28 for test purposes w/o gripping), 17 transfers, 17 back transfers, and 31 drops. There were vastly more drops than transfers because the system was tested separately. The entire process as shown in Fig. 8 could be stabilized, but shows still high potential of improvement.

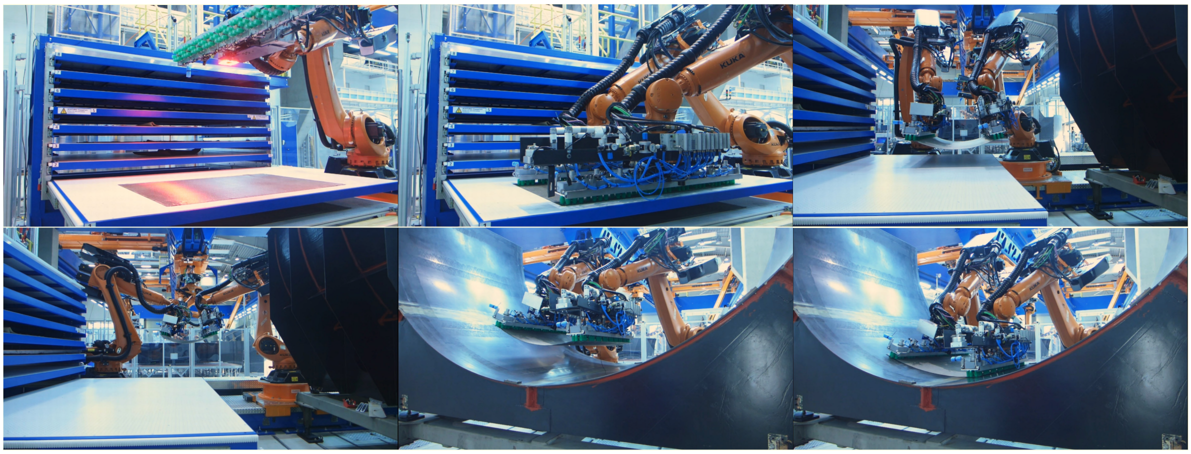

Fig. 8. System test with detection, gripping, transfer, and dropping.

Bugs were encountered as expected in interfacing the system parts and in the MES that had undergone a major revision for addressing multiple robots. The test-phase was completed with a successful technology demonstration with five cut-pieces.

6. Conclusion

The ability to produce a generic airplane part fully automated and autonomously working with multiple robots in a complex environment was demonstrated on a set of five cut-pieces. Whilst the demonstration was carried out on only five cut-pieces there were hundreds of repetitions in which the system performed well and finally showed good stability. Especially remarkable is the good performance of the path planner for the five scenarios. Since there is still work on the production system as well as the collision control the authors for the moment decided not to repeat the complete layup, which was already shown to be possible with a non-autonomous approach [3]. It was successfully shown that the system can perform a pick-and-place process autonomously while having only a generic description and a CAD model of the robot cell. Since further results concerning reliability and accuracy are expected, the processing of the entire plybook is intended for fall 2017. Also work on the system architecture is planned in order to enhance flexibility by extending the current implementation to a fully network based task oriented architecture.

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