# SMART SENSORS FOR AUTONOMOUS ROBOTIC PANEL ASSEMBLY

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## ABSTRACT

Manufacturing of a typical aluminium airframe panel involves the assembly of a couple of stringers and several dozens of clips. The stringers have to be mounted to the skin by riveting, while the clips are “glued” by using a fast hardening sealant. Though there are stringers and clips of identical geometry, there is too much part variation to make automation an easy task, and since tolerances are introduced by sagging manual work is still state of the art in order to cope with this.

The paper is about the implementation of a computer vision sensor system that is capable of identifying individual clips by their CAD-drill hole pattern, determine the clips’ position and allow a robot to correctly pick and place them regardless of positional tolerances. In addition to that, a high accuracy drill hole detector that enables to correctly pick and place stringers and compensates the sagging effects, has been implemented. To ensure the quality of the detection processes the position of the individual parts have been investigated by a structured-light 3D-Camera. Within the paper the involved measurement technologies and the robot calibration are focused. An overview of the entire process chain is also given as well as an outlook to future applications in related areas.

## 1. INTRODUCTION

High variant diversity, low quantities and rising unit labour costs are upcoming challenges in the aerospace industry. Therefore, there is a need for fully automated, flexible and autonomous assembly processes. On the use case of an aerospace panel assembly we demonstrated the feasibility of a fully automated autonomous robotic production.

### 1.1 Autonomous panel assembly process

Panel assembly is a fundamental part of aircraft construction. Regarding the low quantities in combination with the variant diversity it is necessary to combine or integrate several production steps to achieve an effective usage of the production equipment and reduce waiting time. One concept to match these requirements is a multicell. The cell must be able to perform and control not one or two process steps within panel assembly but the complete process chain. In total, eight processes are involved in this application, including cleaning, activation, sealing and pre-assembly of both clips and stringers, which have to be started and adapted to autonomously.

### 1.2 The need for smart sensors

For process control with different variants, smart sensors serve two purposes. On the one hand they help to reduce tooling costs considerably, since component positions can be detected and readjusted in flexible low-cost toolings. On the other hand, quality characteristics can be detected through data acquisition and serve for automatic verification.

For our application we decided to use a production integrated 2D-camera based sensor for both stringer and clip drill hole detection and a 3D structured light camera as quality control for ensuring correct placement of the clips. Because of the tight schedule the 3D-System could not be integrated in the process during the project but was tested on a separate test bed and may be integrated later.

## 2. EXPERIMENTATION

### 2.1 Robot cell layout

The pre-assembly cell consists of a linear axis with two industrial robots as well as a fixture for the aircraft skin and a material supply trolley (Figure 1). In addition, the cell contains several tool change stations for the different end-effectors of the individual processes.

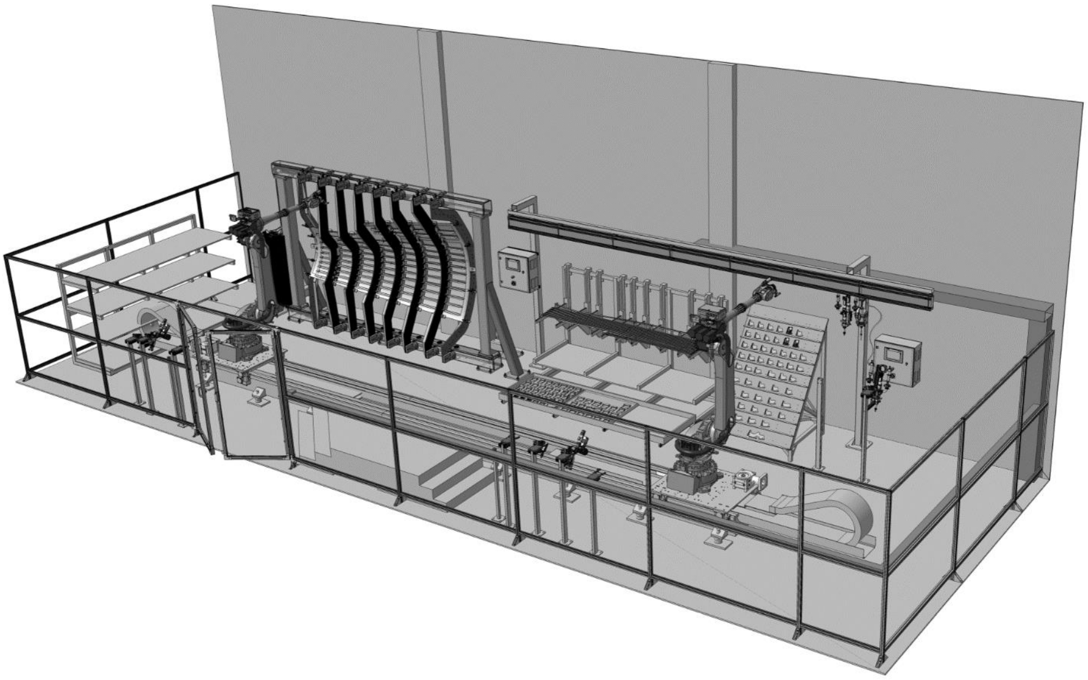


*Figure 1: Robot cell layout*

The fixture for the skin is capable of dealing with all kind of variants, just like the material supply trolley.

### 2.2 Control system concept

The robots are controlled using a Sinumerik 840D, allowing to simulate the offline programmed NC-Code completely beforehand with the Virtual NC-Kernel VNCK [1]. All trajectories and processes can be checked virtually with the simulation tool VZM [2]. All process-specific deviations are then readjusted by the camera system. Therefore, it is not necessary to teach specific positions. The numerical control triggers the camera system to take a picture which is evaluated on a connected workstation. The process deviations are transferred to the numerical control within a defined handshake via OPCUA.

### 2.3 Camera sensor system layout

The camera system consists of two 20 Megapixel IDS GV-5800 SE color GigE-vision cameras [3] with a common illumination ring. The first camera is equipped with a 12mm lens for a wide field of view to detect clips while the second camera has a 75mm lens for a narrow field of view to ensure accurate detection of the stringer drill holes. Both lenses are equipped with polarizing filters to filter out direct reflections of the illumination. The illumination is a white LED ring powered by a flash controller to ensure ambient light independent illumination of the camera field of view. A polarizing filter on the flash ring oriented at 90° to the filters on the lenses ensures that there are no Fresnel reflections from the LED ring on the detected surfaces. Image acquisition, evaluation and communication with the NC controller via OPCUA was implemented in Python by using the manufacturer specific library ids peak for acquisition, OpenCV 4.5.2 for image undistortion [4], evaluation and visualization and opcua 0.98.13 for communication with the NC.

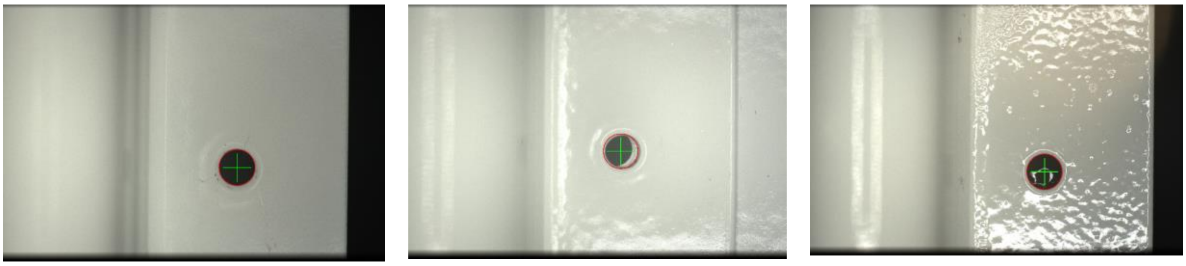
### 2.4 Detection software

In order to determine the clip position we decided to do a blob detection of the drill holes in combination with a least squares fit against the CAD data of the actual clip (Figure 2). To automate process data generation a CATIA-VBA script was used to extract data of the drill holes from the CAD model. The script iterates over every clip and extracts size and position in relation to the respective process coordinate system and exports them to a process readable file.

*Figure 2: Image of clip (left) and the lest squares fit results (right)*

Since the clip is supplied in a shadow board we could rely on the hole being either red or blue (not shown), and a simple blob detector [5] was found to be sufficient for detection. The a.m. drill hole positions of every clip plus an additional reference frame are supplied in a csv-file and extracted according to the clip id (HTZ) provided by the OPCUA-server before detection. Free parameters for the least squares fit are the x- and y distance between reference frame and image centre, the frame’s rotation and a scale factor to compensate minor variations of the working distance.

Concerning the detection of the stringers drill holes we encountered a more complex situation, that displayed the drawbacks of blob detection when there is no perfect control over the background. We found three different situations, namely a free drill hole before the initial stringer pickup, a drill hole that is partially occluded by the underlying drill hole of the skin while setting the rivets and a hole where the sealant covers the hole’s clearing (the sealant may also only partially cover the clearing) (Figure 3). The blob detector we implemented for the clip detection proved to be of insufficient accuracy for the latter two cases, and we had to move on to another approach.

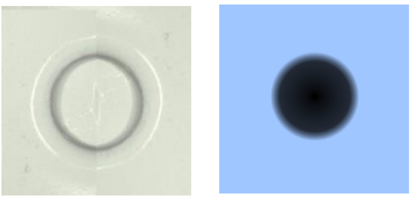


free hole, perfectly aligned polarizers

partially occluded hole, very slightly misaligned polaritzers

Hole with sealant, slighly misaligned polarizers

*Figure 3: Three basic types of background make blob detection unreliable*



pattern

mask

*Figure 4: matching with a mask*

Template or pattern matching is a technique commonly used to detect known patterns in images, and a remarkably robust detection algorithm. For our special application we used a template matcher based on the normalized cross-correlation [6] with a completely occluded drill hole as pattern in combination with a gaussian mask, which reduces the weights of the centremost area gently towards zero. This means that the drill hole edges and the surrounding area (coloured in blue as a guide to the eye) are taken to account completely while the centre part gets less and less weight in the calculation depending on the distance to middle. Further, the gaussian mask tends to centre the detection result with respect to the drill hole, what is a desirable extra effect. With this approach we reached a 100% coverage with more than 400 images taken.

### 2.5 Hand eye calibration

In order to allow correct gripping of the clips and accurate riveting the camera has to be calibrated with respect to the robot. Hand eye calibration (HEC) is state of the art when it comes to operating a robot and a camera in the same coordinate system [7]. Targets are imaged in known robot poses and finally the 3D-transformations between camera and robot are computed. Since our use case incorporates a fixed detection position and an image plane parallel to the gripping plane, we can greatly simplify the HEC-process and, at the same moment, enhance accuracy. For the process boundary conditions see Figure 5.

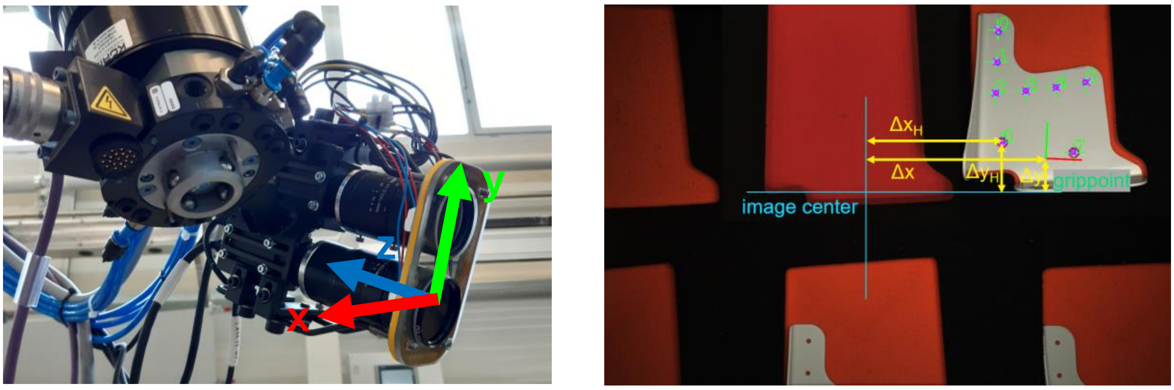


*Figure 5: Simplified, robust hand eye calibration*

We made good experience with the following alternative procedure:

1. Position a calibrated measurement tip on the robot above a selected drill hole (here: hole #6, compare Figure 5 right). Whilst moving the tip gently further into the shadow boards soft foam the clip is centred with respect to the tip.
2. Move perpendicular to the image plane into the z-direction to the desired distance for detection and save the detection point $P_d$.
3. Change the tool from tip to camera and reposition to $P_d$ and turn the camera so that the x- and y- directions are parallel to the image directions (here: x and y are rotated, compare Figure 5).
4. Acquire an image of the clip plus a steel tape measure to perform a scaling calibration (pixels per mm) and the residual angular error $\Delta\varphi_0$ in the python script. In a second image determine the zero distances $\Delta x_H$ and $\Delta y_H$ of the selected drill hole by using the position of the hole measured by the script.
5. Determine the correct orientation and sign by moving the robot and taking images
6. Insert the results in the python script in order to allow the script to return the deviation from zero and the rotation angle.
7. Now the script returns the x and y deviation of the grip point and the rotation angle
8. As an alternative, the corrections may be done in the NC in order to have a single point of truth.

The advantage of the a.m. procedure is its simplicity with the given equipment and the possibility to do an automated drift correction later on. We didn't cross-check with a standard HEC, but it has to be assumed that we surpass the reachable accuracy because we only use relative positioning very close to a fixed point, while the standard HEC makes use of the complete kinematic chain of the robot. In this regard using a conventional HEC is some sort of absolute positioning, while we make use of the robot's repeatability, which is one to several orders of magnitude better than absolute positioning.

## 2.6 Quality control sensor

A Zivid One+ M structured-light 3D camera [8] was used as a quality control sensor to record and evaluate point clouds in order to ensure proper component alignment. Compared to the high accuracy Leica T-scan sensor system, the Zivid camera even delivered slightly better results when comparing planes relative to each other. Figure 6 (bottom) visualizes the normal vectors of each clip. As an optimal result all planes would be aligned.

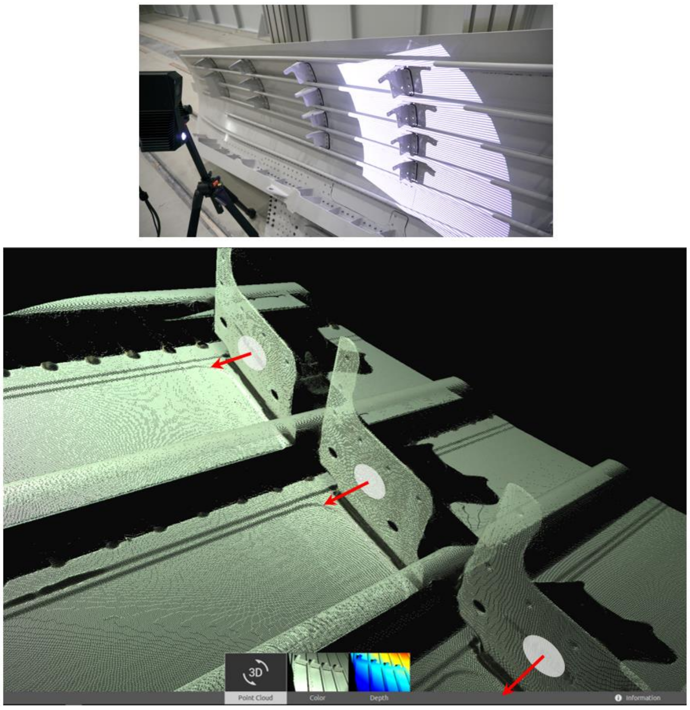


*Figure 6: Measuring with Zivid camera (top), orientation of clips (bottom)*

# 3. RESULTS

## 3.1 Sensor system reliability

The sensor system worked well in our tests and proved reliable with more than 400 stringer drill hole detections and more than 100 clip detections with various clips without any errors and perfect accuracy. From time to time a recalibration seemed to be necessary, but we couldn’t track down if it is a general necessity or more due to the ongoing commissioning of the production line, so this has to be monitored and possibly an automated recalibration must be implemented. Also, we carelessly didn’t secure the polarizers with screw lock and thus needed to realign one of the four as the images got brighter and brighter. Main issue remained the overall reliability of the python software, especially concerning the network connectivity, which indeed made a restart necessary every couple of days, what is not desirable for a production line and has to be improved. Nevertheless, the project time was too short to overcome this mid-term instability so this remains a to do for the future.

## 3.2 Process stability and accuracy

As the camera system is used in the same robot pose as the process is performed, the robot accuracy is compensated very well. Therefore, it is possible to insert rivets (3.3 mm) into predrilled holes of 3.5 mm. Also, the gripping position of clips is examined very precisely. The communication handshake between numerical control and workstation prevents undefined states and ensures the process reliability.

### 3.3 3D-Measurement results

Point clouds of the clips mounted in the skin were taken. The point clouds were then converted to a surface selection, which is shown in Figure 7. Thereby the clips can be separated from the rest of the point cloud, and the position and the boundaries of the clips can be finally determined.

In order to obtain the exact position of the different clips, normal vectors for every n-th point of the point cloud were calculated (Figure 8). With the help of these vectors a recognition of the clip's position relative to each other can be simplified. Orientation and alignment can be deduced by vector comparison and averaging in the next step.

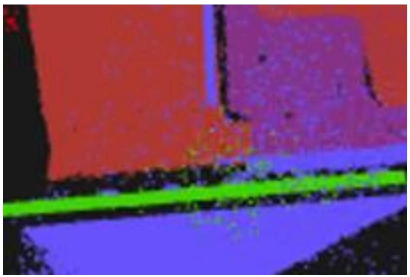


*Figure 7: Surface selection*

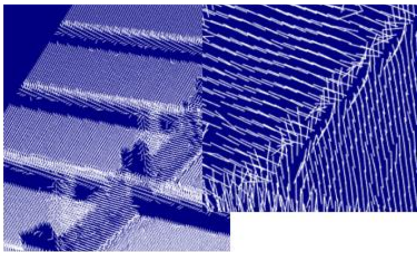


*Figure 8: Normal vectors*

## 4. CONCLUSIONS

On our flexible and autonomous production system we demonstrated a reliable sensor guided process for aerospace panel assembly. A completely digital process chain from CAD to the robot system with a continuous process simulation and integrated smart sensors proved to be a viable concept for flexible automation. The developed production process and especially the integrated detection system will be an essential enabler for future production concepts in aerospace industries. The most important characteristic of the system is its flexibility to adapt to various tasks in order to enhance production flow and to reduce downtimes. Future work should include the integration and automation of the quality control by 3D imaging as well as a database for measurement documentation.

## 5. REFERENCES

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