Optimized Inline Quality Inspection of Carbon Fiber-Reinforced Polymer (CFRP) Components Using Structured Light 3D Imaging.

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1. Abstract

The aerospace industry is undergoing significant transformations, with carbon fiber-reinforced polymers (CFRP) emerging as one of the most critical lightweight materials. Despite their advantageous properties such as high strength-to-weight ratios and corrosion resistance the manufacturing of CFRP components remains complex, costly, and prone to higher tolerances compared to metallic parts. These challenges necessitate continuous optimization of production processes, particularly in quality assurance. One promising approach lies in automated inline quality inspection (QI), which enhances process stability, reproducibility, and efficiency by minimizing human error and variability. Effective automation requires reliable and high-precision measurement technologies, particularly for critical features such as holes and geometric elements in CFRP components. A key obstacle in automated inspection is the accurate detection and measurement of features, especially when optical surface reflections interfere with sensor accuracy. CFRP surfaces often exhibit irregular light scattering, leading to false positives, missed detections, or incomplete measurements, which compromise inspection reliability. Structured light 3D cameras present a robust solution, combining depth sensing with high-resolution imaging for precise feature recognition. This paper examines the application of structured light-based 3D cameras for detecting and measuring holes in CFRP components, focusing on overcoming challenges posed by surface reflections. The process utilises advanced algorithmic approaches to ensure accurate feature extraction, including edge detection, surface roughness compensation and adaptive thresholding. Once features are identified, holes are automatically located, enabling real-time defect detection and process correction. Once the holes are detected, work can continue quickly and a comparison with CAD on tolerances is possible. The findings demonstrate that structured light 3D imaging, when paired with optimized computational methods, provides a scalable and precise solution for CFRP quality assurance. By automating critical inspection tasks, this approach reduces production downtime, minimizes material waste, and enhances overall manufacturing efficiency a crucial step toward advancing lightweight aerospace structures.

2. Introduction

This paper aims to summarise the current state of the art in point cloud processing using various state-of-the-art algorithms, and to present them in a modular format so that they can be used individually or in combination. The aim is to enable fast and straightforward hole and feature detection. This is essential in the manufacture of complex components and applicable across all industries, whether in aircraft construction, automotive manufacturing or aerospace. In this paper, the process is tested and evaluated using a CFRP demo component. As CFRP components will play a significant role in the future – and indeed already do – CFRP components also present specific challenges as they exhibit both absorption and reflection effects of light. Furthermore, the targeted capture and generation of point clouds is not always straightforward. Currently, a laser tracker guided laserscanner is often used as the standard method, which is significantly more expensive than 3D cameras. The effort involved in the measurements is also greater and takes a considerable amount of time. The aim of using 3D cameras is to optimise the time and process, as the cameras are to be integrated directly into the production processes. This eliminates the need for an external measurement step and saves a considerable amount of time. However, such inline quality control must be carried out quickly and in parallel. The experiments are to be carried out without the use of 3D scanning sprays or other tools to help generate better images.

First, frustum culling is performed to reduce the size of the point cloud and make it easier to handle. The normals are then calculated and the planes assigned. These planes are sorted into the relevant planes containing the holes or features. Threshold values are specified and clusters extracted to identify the holes. Planes are created around the points to form the hole. Finally, for better recognition of the hole planes, a circle is fitted into the hole.

3. Preparation and submission

3.1. Research context

The topic of hole detection and feature recognition is a recurring and important theme in projects, and there are various approaches to it. The aim of this research project is to summarise the topic and the individual programmes that have been developed and are currently in use, and to combine them into a coherent programme (algorithm), thereby enabling holes and features to be detected quickly and effectively in a wide variety of applications. The programme will have a modular structure and incorporate various algorithms that reflect the current state of the art.

As many different programmes are currently used in various applications and a time-consuming transformation from 3D to 2D data and subsequently back to 3D data is often necessary, the focus here is on immediate detection in 3D point clouds. This is a method that allows product inspection to be carried out very quickly and efficiently without the need for complex laser scans or the use of external test benches.

A paper from 2024 [1] also examined various 3D cameras and presented an accuracy comparison. Measuring CFRP components poses a particular challenge, as the surfaces often exhibit reflections and/or light absorption effects.

In this paper the experiments were carried out using the Zivid 2+ M60 that utilises structured light. The Zivid 2+ M60 is an industrial colour 3D camera for robot control and image processing. It was specifically developed to enable industrial robots to see with extreme precision and in a manner similar to human vision. [2]

Using a range of algorithms and mathematical methods, the study investigates whether rapid hole detection and feature recognition are possible in a CFRP demonstration component, and what difficulties may arise. In this context, a demonstration component is captured using a 3D camera.

Advantages:

- The combination of different algorithms and methods leads to higher accuracy in hole detection
- The method is efficient and suitable for the automated processing of large amounts of data.
- The detected holes and features can be processed further in a targeted manner to enable precise interventions in 3D point clouds.

3.2. Experimental Setup

The 3D camera is mounted on a robot (as seen in Figure 1) to make it easier to adjust the distance and angle relative to the demonstration component. To secure the component in place it is clamped down in a holding device.

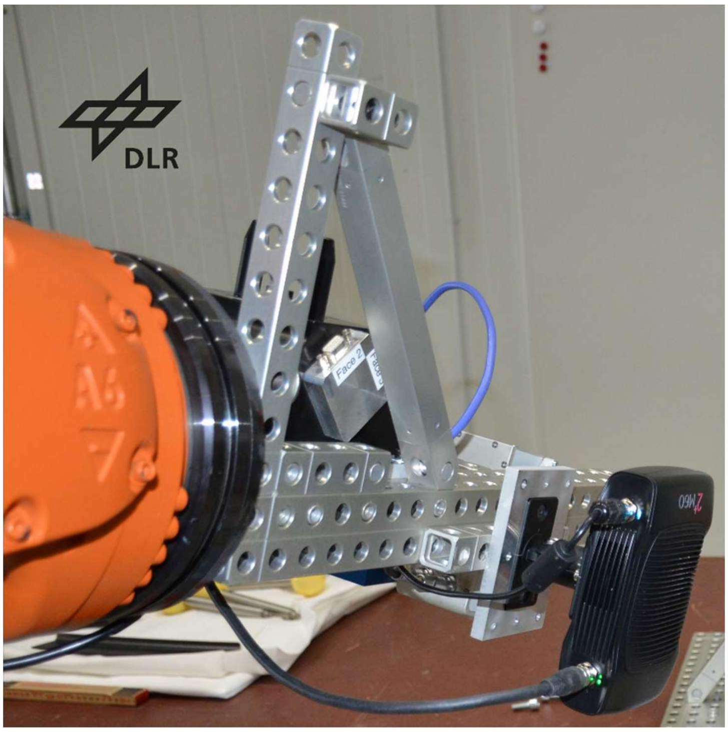

Figure 1 End-effector with camera

During measurement of the component the distance to the component is approximately 450 mm. If possible, the camera should not be pointed at exactly 90° to the component. It is often better not to point the Zivid 3D camera at a component at exactly a 90° angle (perpendicularly), as this causes direct reflections (projector glare) on shiny or metallic surfaces. Such blooming makes parts of the image unreadable. A slight angle deflects the reflected light away from the sensor. [3]

The quality also depends on the camera settings; in this experiment, the images were captured using the standard settings WIDTH 1224 HEIGHT 1024. The 3D point cloud shown in Figure 2 has been processed using frustum culling. Frustum culling reduces the point cloud points recorded by the camera´s field of view. What remains is a point cloud that mainly contains the relevant areas, thereby significantly reducing the amount of processing power on the GPU and CPU. In Figure2, the entire point cloud is shown on the left, and the framed area in green is the section that is retained and used for further processing. The result of this frustum culling is depicted in the image on the right. This significantly reduces the number of points and the computation time for each step.

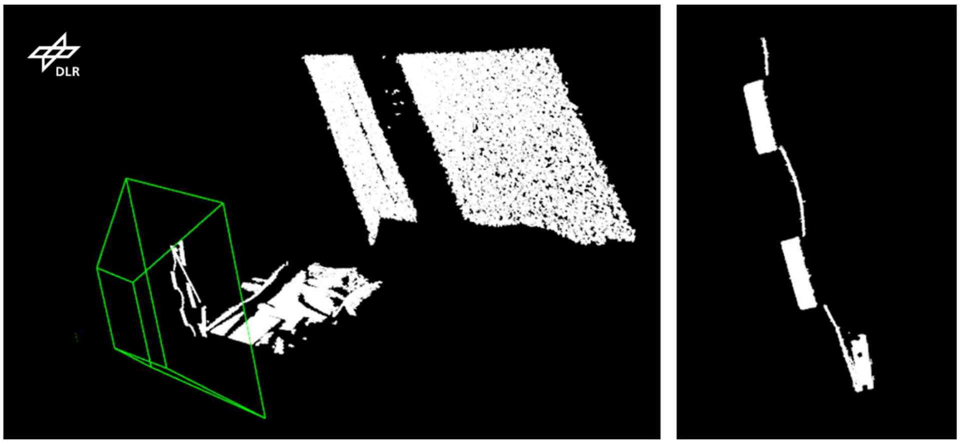

Figure 2 Point cloud with frustum culling

As the camera is mounted on the robot and the demonstrator's position is known in the CAD model, the parameters for frustum culling can be determined in advance. This allows the point cloud to be automatically cropped during the measurement process. Based on the robot's position, the corresponding frustum is selected and the point cloud is reduced.

The reduced point cloud contains all the necessary information to extract the holes. First, the search space is further restricted to limit the area to the two surface segments containing holes. Figure 3 shows the two surface segments, each with a hole, in the right-hand image.

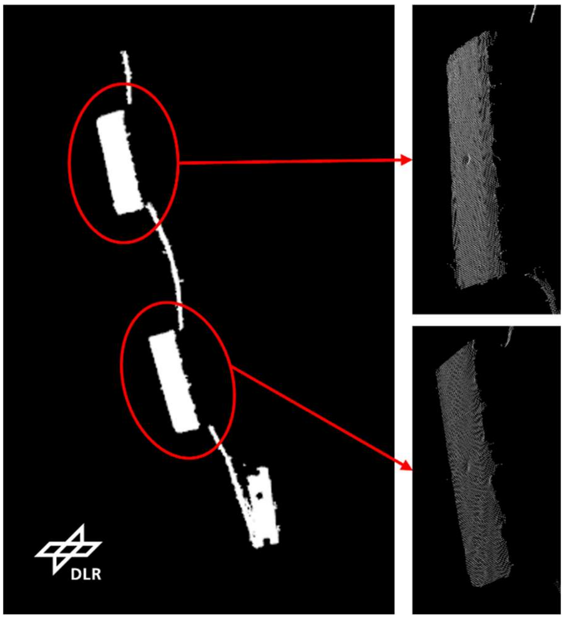

Figure 2 Point cloud after frustum culling

3.3. Calculation of normals and finding planes

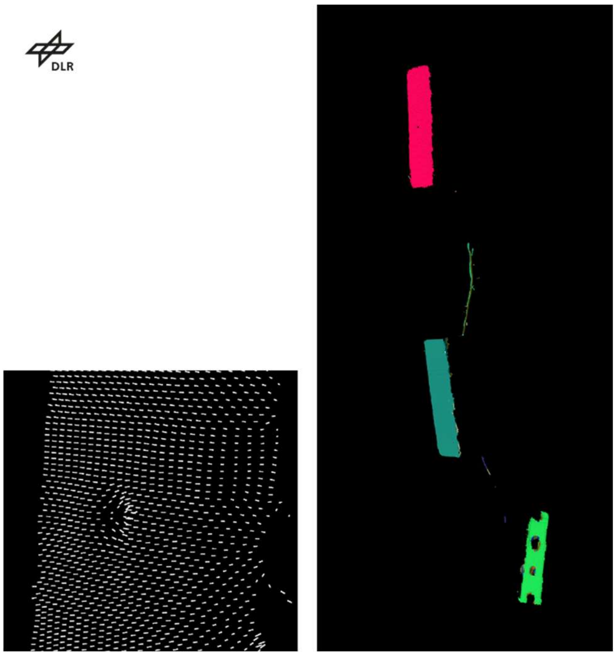

Figure 3 Normals calculation and finding planes

The two relevant surface segments of the demonstrator component can be identified by calculating the normal vectors at each point in the point cloud and subsequently applying the *RANSAC* algorithm. To calculate the normals, a suitable value for the neighbourhood is defined. Based on this neighbourhood, the normal vector is determined for each point using covariance matrix analysis. The result is shown in Figure 4 on the left. The PCL library provides a *RANSAC* implementation capable of detecting planes. The right-hand side of Figure 4 illustrates the different planes found using colour coding. The two relevant planes are coloured red and green.[4]

3.4. Selecting the relevant layers and colour coding the point cloud

Each plane consists of points and forms a point cloud. For each of these point clouds, the eigenvalues are determined using a covariance matrix. By comparing the three eigenvalues with one another, it is possible to draw conclusions about the shape of the point cloud. Using these sphericity values, it is possible to identify the red and dark green planes. The red plane is depicted in the first (left) image of Figure 4 and the dark green plane in the third image of Figure 4.

For each of the two planes, colour values are assigned to the points in the second and fourth image of Figure 4. These colour values make the so-called planarity visible. For each point in the point cloud, planarity indicates the extent to which it lies in a plane relative to a specific neighbourhood. Eigenvalues and eigenvectors are again used for the calculation. The neighbourhood is a parameter and can be adjusted as required. Planarity is not the only feature that can be used; other features can also be calculated and, if necessary, exchanged for or supplemented with planarity.

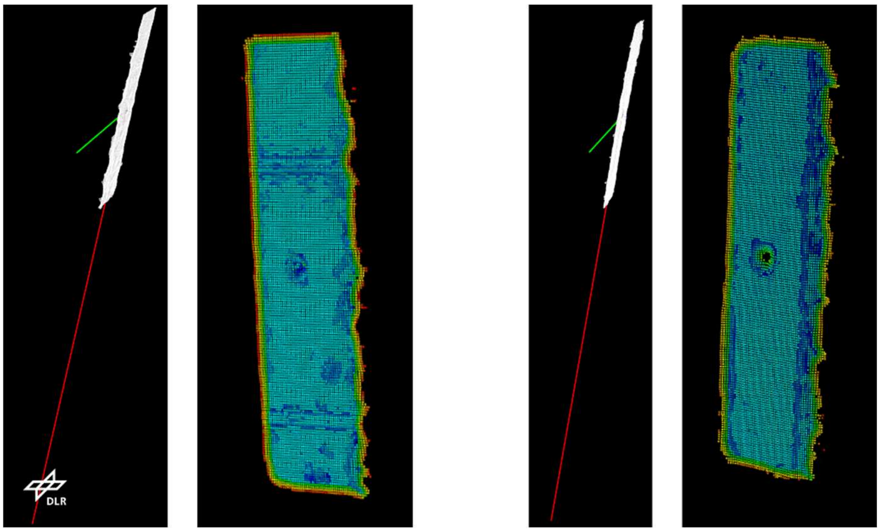

Figure 4 Colour coding the planarity values of each point

3.5. Set a threshold, extract clusters and use them to identify holes

The following is shown merely as an example for the first point cloud (previous Figure 45). The colour values for flatness are filtered using a threshold value, resulting in the image on the left of Figure 6. To identify the hole, the clusters are extracted using a suitable algorithm in this case an euclidean cluster extraction algorithm which is part of the PCL library. In the image at the bottom right, the hole is identified as a separate point cloud. This is the first key objective of the entire process so far.

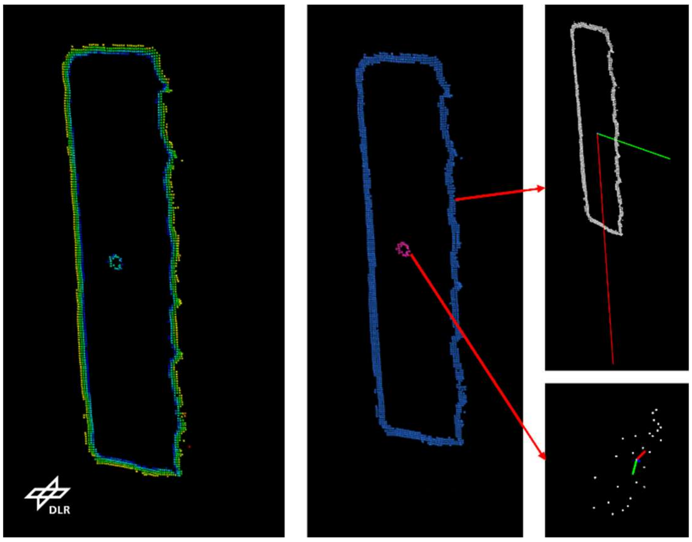

Figure 5 Clustering the points

3.6. Create a plane based on points in the immediate vicinity of the hole

Points are now selected around the hole to define and set up a plane. This is done here using bounding boxes, marked with red in Figure 67, but can also be determined using a different method, provided that points are selected around the hole accordingly. The image on the far right in Figure 6 shows the plane based on these points.

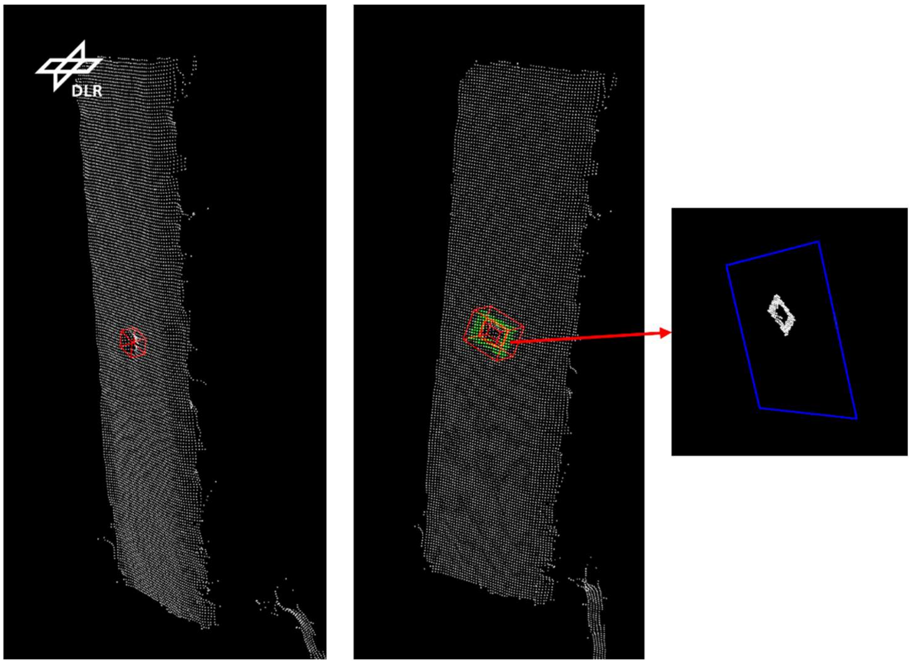

Figure 6 Plane created based on surrounding hole points

3.7. Projecting point clouds onto a plane and fitting a circle

As the points representing the perforated wall on the inside (red dots in the left-hand image in Figure 78) are often only present on one side due to the camera's angle of view, a cylinder would be fitted crooked. To avoid this, and since we know that the perforations are perpendicular to the surface, the points are projected onto the plane (green dots on the blue plane in the illustration below). A circle is fitted using the points projected onto the plane. The green circle in the right-hand image is shown as a cylinder for clarity.

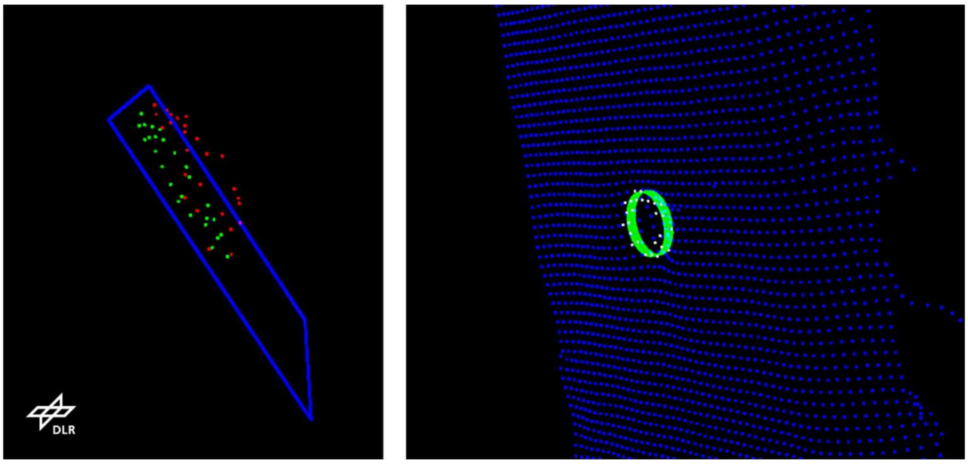

Figure 7 Fitting a circle

4. Summery and outlook

The initial tests were a complete success. We were able to quickly generate images of components and carry out hole and feature detection. The results were not easy to achieve, as the challenges posed by the CFRP material were enormous; glare, reflections and light absorption repeatedly distorted the measurements and made them difficult. However, by adjusting the angle and exposure settings, we managed to generate very good images which could subsequently be reproduced under different lighting and environmental conditions. When taking the images, it was initially possible to do without aids such as 3D scanning sprays for the component's surface. This is a decisive advantage as component cleaning is no longer necessary and the components can be used in the next process step without requiring further treatment. The enormous time saving compared to other measurement methods is significant, as this step for hole alignment took only a few seconds. Depending on the size of the component, the measurement may take longer, but it is always a significantly shorter time than with other methods e.g. using a laser tracker.

This enables faster and more efficient production with integrated quality assurance. A key advantage is the modular design, which means that the results of each individual step can also be used for other purposes. As soon as holes are part of the component, the recorded point cloud can be used for a wide range of applications for further processing. For example, deviations and tolerances can be quickly and easily compared with the CAD data using the recorded point cloud. However, this also presents a certain challenge in terms of speed. This is already being utilised and will lead to a further publication shortly. The aim is to achieve faster and more cost-effective integrated quality assurance.

5. References

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[2] Zivid, ‘‘Zivid 2+ M60 Technical specification”, 09 Mai 2026

[3] Zivid, “ZIVID KNOWLEDGE BASE documentation” 28 Mai 2026

[4] PCL, “Estimation Surface Normals in a PointCloud”, 25 Mai 2026