A comprehensive solution for inspecting cable brackets in aircraft based on augmented reality and deep learning

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***Abstract*—The reliability of the avionics system is crucial to the safety of aircraft. In the process of aircraft final assembly, the avionics system is fixed by tens of thousands of cable brackets. In order to guarantee the reliability of the avionics system, cable brackets need to be inspected before the assembly of the avionics system. Such an inspection task is usually performed by manual verification with CAD models, hence is time-consuming, labor-intensive, and error-prone. In order to improve inspection efficiency, many researchers attempt to develop automatic inspection systems for aeronautical mechanical assemblies. However, cable brackets are numerous and ubiquitous all over the aircraft, so cable bracket inspection is quite different from other aeronautical mechanical assemblies. In this paper, a comprehensive solution is proposed for inspecting cable brackets in aircraft. Firstly, the general architecture of the cable bracket inspection system is proposed based on augmented reality and deep learning. Especially, adaptive inspection solutions based on 2D/3D vision are proposed for aircraft structures with different geometrical features. Then, the prototype system is deployed on two kinds of platforms. One is an AR glasses-based 2D visual inspection system for 2D planar structures, and the other one is a handheld tablet-based 3D visual inspection system for 3D curved surface structures. Finally, the verification experiments are carried out on the C919 aircraft final-assembly workshop, and the experimental results show that the approach is promising for large-scale industrial applications.**

***Keywords*—visual inspection, cable brackets, aircraft assembly, augmented reality, deep learning**

I. Introduction

The avionics system is one of the most critical systems affecting the flight safety of aircraft [1], and the layout of such a system is like a intricate neural network connecting various avionic components. In the process of aircraft final assembly, the avionics system is fixed by tens of thousands of cable brackets [2]. In order to guarantee the reliability of the avionics system, cable brackets need to be inspected to identify misassemblies before the assembly of the avionics system. However, the traditional inspection method for so many cable brackets is to manually verify with CAD models, which is not only labor-intensive but also massively inefficient. Taking the large commercial aircraft C919 made in China as an example, with the continuous improvement of aircraft production, the market has put forward higher requirements for aircraft manufacturing efficiency.

In order to improve assembly inspection efficiency, many researchers attempt to develop automatic inspection systems for aeronautical mechanical assemblies. Biagio et al proposed a multi-camera inspection system for CAD model checking based on support vector machine [3]. However, aeronautical mechanical assemblies need to be placed in the middle of the camera system, which is not suitable for widely distributed cable brackets. Ben et al introduced an automatic inspection method based on 2D vision, they developed a robotic inspection system for aircraft engine [4]. However, they adopt a traditional image segmentation algorithm named Canny edge detector, which can not handle assembly scenarios with many interference targets. In addition, due to the complexity of the internal structure of civil aircraft, the robotic system is not suitable for assembly scenarios with uneven floors or narrow sections. De et al developed an AR-assisted fuselage cable brackets assembly system [5]. In addition, Airbus developed an AR-assisted cable bracket inspection system named Smart Augmented Reality Tool (SART) [6]. In contrast to the robotic inspection system and the multi-camera inspection system, the AR-assisted inspection system is more intuitive and portable. However, SART only superimposes Digital Mock-Up over real aeronautical mechanical assemblies, and it still needs operators to manually compare and label.

Different from other aeronautical mechanical assemblies, as shown in Fig.1, cable brackets are numerous and ubiquitous all over the aircraft from the fuselage with uneven floors to the narrow center wing box. In this paper, a comprehensive solution for inspecting cable brackets in aircraft is introduced based on our previous researches [2] and [7]. Firstly, the general architecture of the cable bracket inspection system is proposed. Secondly, an AR glasses-based 2D visual inspection method is proposed for aircraft planar structures, such as the narrow center wing box. Thirdly, a handheld tablet-based AR-assisted 3D visual inspection method is proposed for aircraft curved surface structures, such as the fuselage. Finally, prototype systems are developed and verification experiments

Fig. 1. Characteristics of C919 aircraft cable bracket inspection.

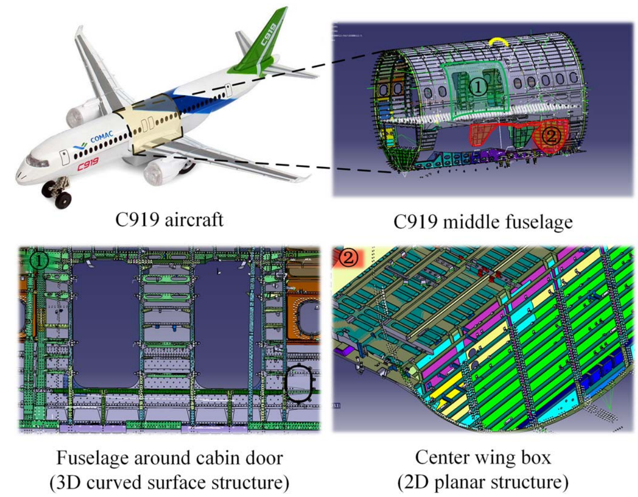


Fig. 2. According to geometrical features of aeronautical mechanical assemblies, they can be classified into 2D planar structures and 3D curved surface structures.

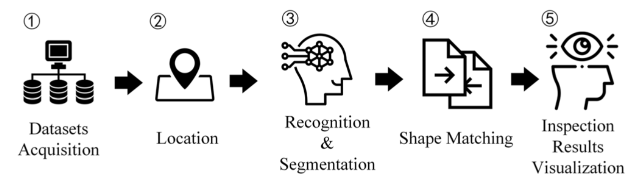


Fig. 3. The general architecture of the proposed 2D/3D visual inspection system.

are carried out on the C919 aircraft final-assembly workshop.

The rest of the paper is organized as follows. In Section.2, the general architecture of the proposed intelligent inspection approach is described in detail. The methodology is described in Section.3. In Section.4, the case study is depicted. Finally, the paper is concluded in Section.5.

II. Architecture

Taking the large commercial aircraft C919 made in China as an example, cable brackets are ubiquitous all over the aircraft from the cockpit, the fuselage, and the center wing box to the tail cone [7]. According to geometrical features of aeronautical mechanical assemblies, they can be classified into 2D planar structures and 3D curved surface structures. As shown in Fig.2, the fuselage is a representative 3D curved surface structure, and the center wing box is a representative 2D planar structure.

For different kinds of aeronautical mechanical assemblies, we propose a comprehensive solution for inspecting cable brackets. For 2D planar structures, such as the center wing box, an AR glasses-based 2D visual inspection method is proposed, which can inspect many brackets at once. For 3D curved surface structures, such as the fuselage around the cabin door, a handheld tablet-based AR-assisted 3D visual inspection method is proposed, which can inspect every cable bracket from any point of view.

However, 2D/3D visual inspection methods have the same general architecture, which is mainly composed of five parts: 1) training datasets acquisition; 2) location; 3) cable brackets recognition and segmentation; 4) shape matching; 5) visualization. The general architecture of the proposed 2D/3D visual inspection system is shown in Fig.3. Firstly, a simulation platform is proposed to generate synthetic realistic training datasets. Secondly, location algorithms are applied to locate cable brackets to be inspected. Thirdly, deep learning-based image segmentation algorithms are applied to recognize and segment brackets. Then, every bracket to be inspected is compared with corresponding virtual brackets captured from CAD models. Finally, inspection results are visualized and labeled with special colors.

III. Methodology

A. Synthetic dataset generation

Fig.4 shows an overview of the developed simulation platform that capable of generating realistic images and corresponding pixel-level annotations, which includes four major steps:

STEP1: CAD model pre-processing. The CAD model in the aviation industry has plenty of design data, manufacturing information, and detailed triangle meshes. Therefore, superfluous meshes are deleted. In addition, some auxiliary tools, such as rivets and pins, are added to the main CAD model.

STEP2: Lighting and material settings. Prakash uses different rendering conditions to allow the deep learning model to learn common patterns of datasets [8]. Therefore, brackets with different materials and random lighting are applied in the scene to ensure robustness.

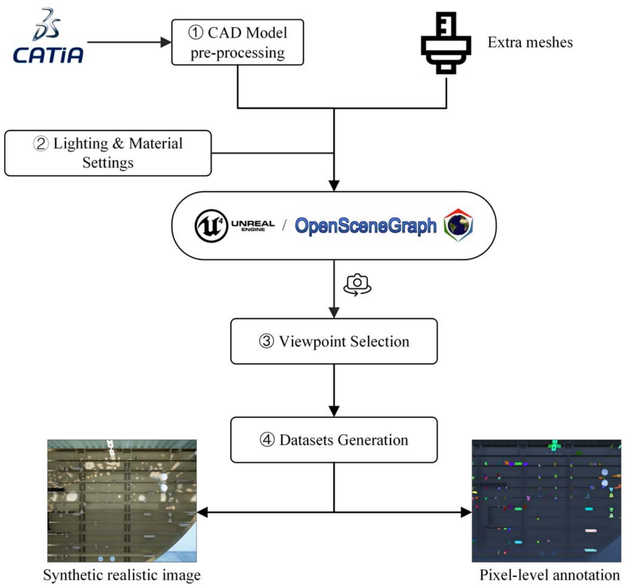


Fig. 4. Overview of the developed dataset generation platform.

STEP3: Viewpoint selection. Taking a picture in a virtual assembly scene needs to avoid being obstructed by other objects. Therefore, a spline curve is fit as the base path by setting a small number of control points in the scene, which ensures that the camera does not collide with other objects. In addition, a random deviation is used to simulate the uncertainty of manual shot.

STEP4: Datasets generation. At each viewpoint, a realistic RGB image is rendered, and the corresponding annotation mask image is generated by rendering brackets with different grayscale values from 1 to N. Then, a color map is used to visualize the annotation mask image. In addition, the related label information is recorded in a YAML file.

B. 2D visual inspection for planar structures

For 2D planar structures, such as the center wing box, an AR glasses-based 2D visual inspection method is proposed. As shown in Fig.5, the proposed 2D visual inspection method based on the AR glasses is mainly composed of four steps:

STEP1: Brackets segmentation. Accurate bracket recognition and segmentation are the prerequisites for bracket inspection. Considering the complexity of the aircraft final-assembly scenarios, deep learning-based instance segmentation, i.e., Mask R-CNN [9], is applied for accurate brackets recognition and segmentation. The input of the Mask R-CNN-based brackets recognizer is the captured brackets image to be inspected. The output of the Mask R-CNN-based brackets recognizer is masks of all brackets.

STEP2: Multi-scale template matching [10]. For 2D planar structures, although frames are repeated structures, the layout of brackets is different. Therefore, a multi-scale template matching algorithm is proposed to locate the current viewpoint. Once the current viewpoint is located, virtual standard brackets corresponding to real brackets can be rendered separately.

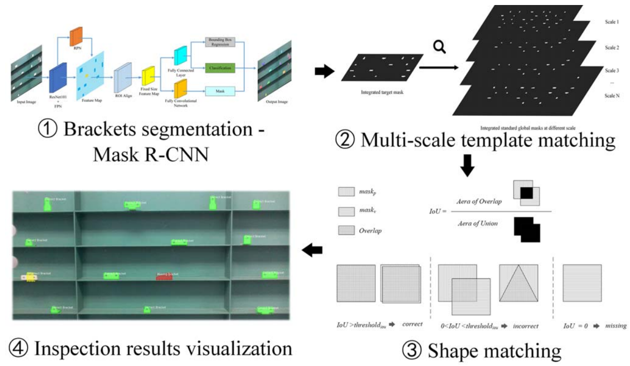


Fig. 5. Overview of the proposed 2D visual inspection method for planar structures.

STEP3: Shape matching. The similarity between the bracket to be inspected and the corresponding rendered virtual bracket is evaluated by the Intersection-over-Union (IoU) [11].

STEP4: Inspection results visualization. Marking every bracket with special colored masks, i.e., marking correct brackets with green color, marking missing brackets with red color, and marking incorrect brackets with yellow color.

More details can be seen in our previous research [2].

C. 3D visual inspection for curved surface structures

For 3D curved surface structures, viewpoint location is more difficult than 2D planar structures and hence needs more computational power. As a result, a handheld tablet-based AR-assisted 3D visual inspection method is proposed. As shown in Fig.6, the proposed 3D visual inspection method based on the handheld tablet is mainly composed of four steps:

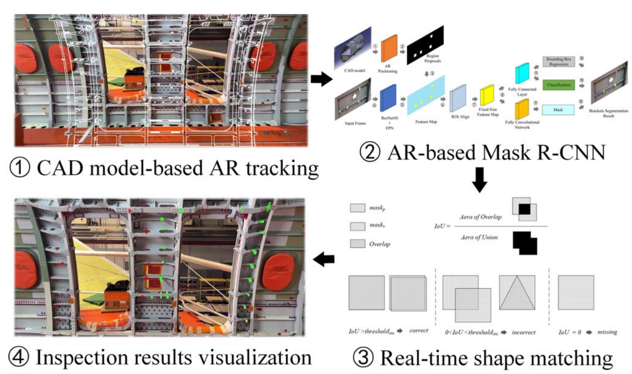


Fig. 6. Overview of the proposed AR-assisted 3D visual inspection method for curved surface structures.

STEP1: CAD model-based AR tracking. Vuforia Model Target [12] is adopted to obtain markerless real-time AR registration and tracking.

STEP2: Real-time brackets segmentation. Different from the above-mentioned 2D visual inspection, brackets segmentation for 3D visual inspection needs to meet the real-time requirement. Therefore, AR-based Mask R-CNN is proposed by replacing Region Proposal Network (RPN) with AR positioning, which provides more accurate and fewer region proposals and consequently improves the speed of the brackets segmentation algorithm. More details can be seen in our previous research [7].

STEP3: Shape matching. This step is the same as the above-mentioned 2D visual inspection from a principle perspective.

STEP4: Inspection results visualization. This step is also the same as the above-mentioned 2D visual inspection.

IV. Case Study

In order to verify the effectiveness of the proposed 2D/3D visual inspection approach, two prototype systems are developed. One is an AR glasses-based 2D visual inspection system for 2D planar structures, and the other one is a handheld tablet-based 3D visual inspection system for 3D curved surface structures.

A. The AR glasses-based 2D visual inspection system

As shown in Fig.7, the AR glasses-based 2D inspection system is verified in the laboratory. The type of the AR glasses is EPSON BT350. Due to the insufficient computational power of the AR glasses, deep learning-based brackets segmentation is deployed on a server. In our previous research [2], verification experiments are carried out, and the inspection accuracy of the AR glasses-based 2D visual inspection system is 90.67%.

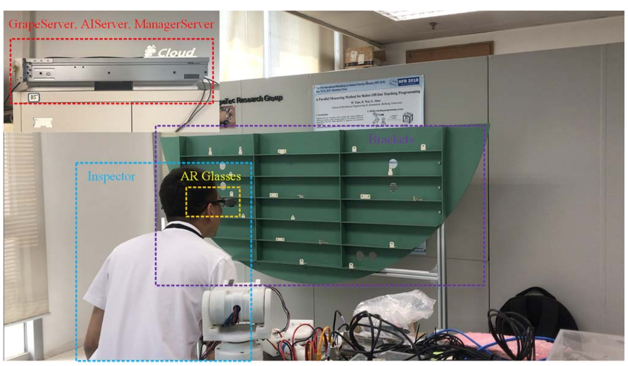


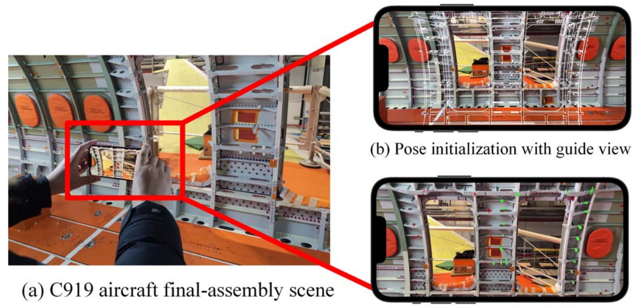
Fig. 7. Deployment of the AR glasses-based 2D visual inspection system in the laboratory [2].

B. The handheld tablet-based 3D visual inspection system

As shown in Fig.8, the handheld tablet-based 3D inspection system is verified in the C919 final-assembly workshop. In our previous research [7], verification experiments are carried out on an iPhone 12 Pro Max, and the inspection accuracy of the handheld tablet-based 3D visual inspection system is 100.0%.

V. Conclusion

This paper proposes a comprehensive solution for inspection cable brackets in aircraft based on augmented reality and deep learning. The main contributions are concluded as follows:



(a) C919 aircraft final-assembly scene

(b) Pose initialization with guide view

(c) Inspection results visulization

Fig. 8. Deployment of the handheld tablet-based 3D visual inspection system in the C919 final-assembly workshop [7].

1) The characteristics of aircraft cable brackets are analyzed in detail. In addition, for aeronautical mechanical assemblies with different geometrical structures, adaptive inspection solutions are proposed.
2) For 2D planar structures, such as the center wing box, an AR glasses-based 2D visual inspection approach is proposed, and a cloud-based prototype system is developed.
3) For 3D curved surface structures, such as the fuselage, a handheld 3D visual inspection approach is proposed for inspecting cable brackets from any point of view.
4) The verification experiments are carried out in the laboratory and the C919 final-assembly workshop separately, and the experimental results show that the proposed brackets inspection method is promising for large-scale industrial applications.

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References

[1] L. Shi, Z. Zhou, H. Jia, P. Yu, S. He, L. Cheng, and Y. Huang, “Fault diagnosis of functional circuit in avionics system based on bpnn,” in *2019 Prognostics and System Health Management Conference (PHM-Qingdao)*. IEEE, 2019, pp. 1–5.

[2] Z. Gang, H. Jingyu, X. Wenlei, and Z. Jie, “A Mask R-CNN based method for inspecting cable brackets in aircraft,” *Chinese Journal of Aeronautics*, 2020.

[3] M. San Biagio, C. Beltran-Gonzalez, S. Giunta, A. Del Bue, and V. Murino, “Automatic inspection of aeronautic components,” *Machine Vision and Applications*, vol. 28, no. 5, pp. 591–605, 2017.

[4] H. Ben Abdallah, I. Jovančević, J.-J. Orteu, and L. Brèthes, “Automatic inspection of aeronautical mechanical assemblies by matching the 3d cad model and real 2d images,” *Journal of Imaging*, vol. 5, no. 10, p. 81, 2019.

[5] L. F. de Souza Cardoso, F. C. M. Q. Mariano, and E. R. Zorzal, “Mobile augmented reality to support fuselage assembly,” *Computers & Industrial Engineering*, vol. 148, p. 106712, 2020.

[6] Testia, “SmartMixedReality,” https://www.testia.com/news/mira-airbus-available-through-testia-smartmixedreality/, 2021.

[7] H. Jingyu, Z. Gang, X. Wenlei, and L. Rvpeng, “AR-based deep learning for real-time inspection of cable brackets in aircraft,” unpublished.

[8] A. Prakash, S. Boochoon, M. Brophy, D. Acuna, E. Cameracci, G. State, O. Shapira, and S. Birchfield, "Structured domain randomization: Bridging the reality gap by context-aware synthetic data," in *2019 International Conference on Robotics and Automation (ICRA)*. IEEE, 2019, pp. 7249–7255.
[9] K. He, G. Gkioxari, P. Dollár, and R. Girshick, "Mask r-cnn," in *Proceedings of the IEEE international conference on computer vision*, 2017, pp. 2961–2969.
[10] H. Y. Kim and S. A. d. Araújo, "Grayscale template-matching invariant to rotation, scale, translation, brightness and contrast," in *Pacific-rim symposium on image and video technology*. Springer, 2007, pp. 100–113.
[11] R. Padilla, W. L. Passos, T. L. Dias, S. L. Netto, and E. A. da Silva, "A comparative analysis of object detection metrics with a companion open-source toolkit," *Electronics*, vol. 10, no. 3, p. 279, 2021.
[12] Vuforia, "VuforiaModelTarget," https://library.vuforia.com/objects/model-targets, 2021.