Augmented reality tracking registration and process visualization method for large spacecraft cable assembly

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Abstract. The new generation of spacecraft has the characteristics of large-scale structure and complicated cable assembly process. In order to meet the needs of the augmented reality process visualization technology in its further application exploration, the two aspects of augmented reality tracking registration and process visualization are now studied. In the large-scale spacecraft cable assembly application scenario, the augmented reality process guidance technology puts more stringent requirements on the continuous tracking range and virtual and real registration accuracy of large space. The 3D process visualization method for cable assembly is optimized to improve the accuracy, quality and efficiency of the operator in process interpretation and implementation.

1. Introduction
Cable assembly is an important task in the overall assembly process of the spacecraft. It is directly related to the normal operation of the electrical equipment inside the spacecraft, thus affecting the overall performance of the spacecraft. Because the automation equipment is difficult to adapt to the complicated cable assembly conditions, the current cable assembly relies heavily on manual operation, and the two-handed coordination assembly action accounts for more than 70% of the total assembly work of the spacecraft[1]. At present, a new generation of military satellites represented by remote sensing satellites, communication relay satellites and navigation satellites are being accelerated. Compared with the previous satellites, they have undergone major changes in the configuration and development status, showing the characteristics of short development cycle, variable technical status, large-scale components, complex cable lines and high assembly quality requirements. The satellite structures and functions have become more complex, and the need for precision operations in tight spaces is increasing. The assembler is required to have a more adequate perception of the operating environment and a higher level of operational skill. At the overall assembly site of the spacecraft, the traditional two-dimensional drawings or fixed kanban systems are used to display the information required for cable laying. The workers operate according to the drawings or the 3D model displayed on the kanban, as shown in Figure 1. This type of method has problems such as low work efficiency, high probability of error, and high learning cost[2].
The application of Augmented Reality (AR) in the spacecraft cable assembly process provides a new way to solve the above problems. Augmented reality technology combines real-life scenarios with virtual objects/information to automatically match cable assembly process information with real-world physical environments[3]. It helps the operator understand the various assembly relationships in the scene and greatly reduces the effort required to move the line of sight between the process kanban and the operator station. It simplifies the operator's interpretation of the process specification through visual and easy-to-understand instructions, which can significantly reduce the cognitive burden of the operator under complex working conditions, improve the operation accuracy, and prevent operational errors. It responds to user's operating intentions in a natural human-computer interaction manner, which can greatly improve the efficiency of two-handed collaborative work. Therefore, the augmented reality based cable assembly process visualization technology can accurately and efficiently guide workers to complete the manual assembly operation of the cable. It helps achieve the synergy and integration of “human-machine-environment” and promotes the development of intelligent satellite assembly mode. The comparison between the traditional mode and the augmented reality process visualization mode is shown in Figure 2.

As early as the 1990s, Boeing used AR technology in the connection of power cables and the assembly of connectors in aircraft manufacturing, saving Boeing a lot of space and cost for storing wiring boards[4]. NASA created a collaborative augmented reality environment where operators can assemble spacecraft through head-up and gesture control through pre-defined parts and virtual tools, which enhances the operator's understanding of the process[5]. Airbus applied the MiRA augmented reality system to the A400M aircraft cable assembly site for cable assembly and inspection. The operators can intuitively obtain the mounting position and assembly information in the virtual and real fusion interface. They then accurately perform installation tasks of complex piping, hundreds of kilometers of cables, and connector[6].

For the new technical requirements generated by the large-scale spacecraft, the augmented reality-based cable assembly process visualization technology needs to improve the technical capabilities according to specific application scenarios. This paper now studies the augmented reality tracking
registration and process visualization for large spacecraft cable assembly, and helps to promote augmented reality applications to further spacecraft assembly scenarios.

2. Technical framework
The technical framework for augmented reality tracking registration and process visualization methods for large spacecraft cable assembly applications is shown in Figure 3.

![Figure 3](image)

**Figure 3.** Tracking registration and process visualization method technical framework.

Augmented reality applications for large spacecraft cable assemblies need to address two key issues of large-scale product virtual and real registration and visualization of process information for specific operating conditions. By identifying the planar markers, the virtual model is registered to a fixed spatial location relative to the marker and an initial coordinate system is established. The current pose data is then passed to the spatial mapping system of the visual SLAM, extending the continuous stable tracking registration range. Then, based on this, the relative posture of the virtual model in space is adjusted by interactive control, and the virtual model is further accurately registered from different perspectives. Through the visual method of virtual and real fusion, the cable assembly path and the electrical connector number and other information are expressed, which fully guides the operator to carry out the manual operation of the cable assembly. Through the virtual and real occlusion consistency control method, the misunderstanding of the visual 3D process is avoided, and the correct implementation of the process intention is ensured.

3. Virtual and real tracking registration method for large spacecraft assembly scene

3.1. Tracking registration technology based on plane markers
With the advancement of computer vision technology, the mark recognition technology based on image feature detection uses a camera to capture a scene containing a marker, and uses image processing and analysis to identify the image in the video stream. On the one hand, by identifying the target image feature as a unique identifier of different objects, the corresponding process model in the database is retrieved to establish a driving relationship between the entity and the virtual process model. On the other hand, according to the correspondence between the image feature points and the target feature points, the camera model is used to solve the relative pose of the camera in the world coordinate system, and then the position of the marker is calculated in real time, and the model is registered to the fixed space position[7].

At present, image feature-based extraction and matching algorithms such as SIFT, SURF, ORB and HOB have wide application and research value. The common problem lies in how to construct fast and robust feature points and descriptors. For example, ORB (Oriented FAST and Rotated BRIEF) algorithm is a combination and improvement of FAST feature points and BREIF descriptors, which has a good response speed in online real-time detection and other applications. Therefore, the image
feature detection algorithm based on ORB is usually a very good choice in the application of image matching and real-time visual SLAM. As shown in Figure 4, the image recognition and matching algorithm is used to identify and locate the planar marker image.

Figure 4. Plane marker tracking and positioning based on image feature recognition.

On this basis, the virtual model is registered to the corresponding area through the pinhole camera imaging model (Formula 1) to realize the virtual reality fusion effect of the augmented reality.

\[ z_c \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = MK \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \]  

(1)

Where \( z_c \) represents the depth of the pixel of the image, \((u, v)\) is the coordinates of the pixel, \(M\) is the internal reference matrix of the camera, \(K\) is the external parameter matrix of the camera, and \((x, y, z)\) represents the three-dimensional space point corresponding to each pixel point. Through this formula, the mapping relationship from any point in the real scene coordinate system to the corresponding position in the two-dimensional imaging plane coordinate system is established. The application of augmented reality technology based on planar marker recognition in large spacecraft scenarios is limited by hardware capabilities, algorithm efficiency and data accuracy. The initialization result of the virtual and real registration is often not accurate enough, and the error of the virtual and real registration is positively correlated with the distance from the preset mark. At the same time, the augmented reality technology using marker recognition alone can't get rid of the limitation that the requirement mark always remains in the camera field of view.

3.2. Tracking registration technology based on visual SLAM

Visual Simultaneous Localization and Mapping (VSLAM) technology constructs a globally consistent environment 3D point cloud model through sensors such as cameras, and infers the motion of the camera and the surrounding environment. The depth information of the image is obtained by the principle of infrared structured light or Time-of-Flight (ToF), and the three-dimensional rigid body motion of the camera between adjacent frame images is calculated in the SLAM front-end visual odometer. The scope of virtual and real tracking registration is extended by the method of visual SLAM. In a feature-intensive area of a large spacecraft assembly scene, the movement of the camera hardly causes the virtual model to drift in real space.

3.3. Integrated tracking registration technology based on marker recognition and visual SLAM

As an improved method, the tracking registration method based on planar marker recognition and visual SLAM technology first uses the RGB-D camera to scan the working environment to reconstruct the scene 3D model. The camera pose is tracked by matching the feature points of the current frame image with the global feature point cloud. The result data based on the marker recognition and positioning is passed to the SLAM coordinate system, and then the virtual model is anchored in the scene space based on the visual SLAM technique. This approach avoids the requirement of visual
marker visibility for the continuous tracking process, thus extending the tracking range with better robustness and accuracy.

On this basis, the six-degree-of-freedom adjustment of the virtual model is allowed with high precision through the interactive interface. For assembly stations in different parts of large spacecraft, the current deviation between virtual and real registration is derived from the error in the recognition of plane markers and the cumulative error of SLAM. By establishing a visual reference between the virtual model and the actual spacecraft/tooling, the virtual model is fine-tuned by six degrees of freedom, which realizes manual reduction of the virtual and real tracking registration errors and improves the accuracy of process information visualization.

4. Process visualization method for assembly guidance of complex cable networks

The spacecraft cable assembly in the augmented reality process mode is mainly performed based on the design model and related information extracted therefrom. It involves aspects such as model building, information extraction, process writing, and on-site display. It is necessary to ensure that the transmission of the cable loading data is complete and reliable, so that the design requirements are fully realized when the assembly is implemented. The existing digital prototype is split and reconstructed for field application requirements, and then it is used as the data foundation of 3D assembly instructions. As shown in Figure 5, the visualization process data is built on the basis of not changing the assembly relationship of the product. By constructing a Bill of Material (BOM) to build a process-oriented digital prototype, it supports the rapid generation of 3D assembly instructions.

4.1. Cable assembly path and electrical connector number visualization

The augmented reality-based assembly process visualization technology provides a new way to demonstrate the assembly process specification. The 3D process information is distributed to the operator's field of vision through a visual interface of virtual and real fusion. The main process information is shown in Table 1.

| Number | Assembly information element                                      |
|--------|------------------------------------------------------------------|
| 1      | Cable number                                                     |
| 2      | Cable information                                                |
| 3      | Electrical connector number                                       |
| 4      | Reserved length at the end of the branch                         |
| 5      | Related product information                                      |
| 6      | Nylon base and cable bracket layout (binding point)              |
| 7      | Equipment and equipment socket layout                             |
| 8      | Power, pyrotechnic cable, etc. are distinguished by color        |
| 9      | Quadrant/direction identification                                |

The spatial location of the cable end electrical connector model is extracted by an automated method, and then the 3D electrical connector number text is displayed at that location. For electrical connectors with close spatial positions, the display text is heavily overlapped in space and has low recognition, as shown in Figure 7 (b). In order to ensure a good 3D process visualization, the existing display methods are improved. The visual optimization process of the 3D electrical connector number information is shown in Figure 6.
Figure 6. Visualization optimization method for electrical connector number.

On the one hand, the 3D text is updated in each frame, so that the text normal always points to the camera direction, and the rotation axis is set to the y-axis to ensure that the text always faces the line of sight. The text normal vector should be: \( \mathbf{R} = \mathbf{B} - \mathbf{A} \). \( \mathbf{B} \) and \( \mathbf{A} \) are the coordinates of the camera coordinates and text instances in the scene, respectively. On the other hand, based on the collision detection method, the pitch of the 3D text is always larger than a specific distance in a specific direction (the diameter of the "rigidbody ball"). Then adding a guide line from the initial position to the adjusted coordinates to ensure good visibility of the 3D text, as shown in Figure 7.

(a) Electrical connector layout is tight.  (b) 3D text overlaps each other.

(c) Automatic adjustment of coordinates based on collision detection.  (d) Redefinition of 3D text coordinate positions.

Figure 7. 3D text visualization based on collision detection.
4.2. Virtual and real occlusion consistency method

The traditional augmented reality effect is simply to superimpose the virtual model in the real scene, and it is difficult to obtain a realistic fusion effect. It is difficult for the operator to correctly judge the relative positional relationship between the virtual and real objects, and the depth anomaly perception has a great influence on ensuring the precise operation[8]. Now based on the "model reconstruction" method, the depth values of the "virtual and real model" are compared. Then, based on the result of the comparison, only the portion of the virtual cable model that is not occluded is rendered. First, the application system synchronizes the real-time spacecraft assembly status (such as the actual state of the components such as the deck, nylon base, and cable bracket) in real time to ensure the consistency of the virtual and real states. The existing spacecraft process model (assembled part) is used as the "real state model" to avoid model reconstruction of the field assembly conditions, saving workload and improving the accuracy of virtual and real occlusion. In the depth test phase of the rendering pipeline process, the depth value of the cable model pixel to be assembled that needs to be drawn is compared with the depth of the corresponding "real state model" pixel in the depth buffer. If it is larger than the value in the depth buffer, then the pixel is not written to any color channel (thus exposing the actual implementation), otherwise the pixel color is changed to the newly drawn pixel color (the color of the virtual cable to be assembled). The processing flow is shown in Figure 8.

![Figure 8](image)

**Figure 8.** Virtual&real occlusion rendering process.

The virtual and real occlusion effect between the spacecraft deck and the cable is shown in Figure 9, which avoids the operator's visual illusion and improves the readability of the process information.

![Figure 9](image)

**Figure 9.** Virtual and real occlusion consistency between the deck and the cable.

5. Conclusion

In this paper, the augmented reality tracking registration and process visualization method for large-scale spacecraft cable assembly is studied, which solves the problem that the traditional tracking registration method has insufficient virtual and real registration precision and limited tracking range in...
large-scale structural spacecraft products. Then, using the optimized 3D visualization information expression method and the virtual and real occlusion consistency control method, the cable assembly process information is fully demonstrated in the implementation process. It effectively improves the efficiency and precision of the operator's manual operation in cable assembly and promotes the development of the intelligent manufacturing mode of spacecraft.

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