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Collaborative robot and mixed reality assisted microgravity assembly for large space mechanism

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Abstract

Gravity balance has a great impact on the assembly and deployment experiment of the large space mechanism to achieve the perfect performance in space. Traditional gravity balance methods have their advantages in the deployment experiment, but not suitable for the assembly process which has a more stringent location requirement. This paper proposed an advanced microgravity assembly method for a large space mechanism. The architecture of the system for microgravity assembly is proposed. The collaborative robot and mixed reality (MR) are integrated into this system, which can realize human-robot collaboration assembly, improve assembly efficiency and reduce errors. The microgravity assembly is realized by the six-dimensional force sensor which makes the robot work in force control and installed at the end of the collaborative robot. The prototype system is verified in the laboratory environment, which provides a new and feasible assembly mode for intelligent collaborative assembly for large complex space products.

Keywords: Intelligent Assembly, Human-machine collaboration, Mixed reality, Condition monitoring, Large space mechanism.

1. Introduction

When the large space mechanisms such as satellite antenna work in space, they are in the environment of microgravity [1]. At the same time, due to their complex structure and high precision, a series of microgravity assembly tests need to be conducted on the ground to ensure their normal use in orbit. However, during the ground assembly process, the assembly force caused by gravity will be generated. This will not only affect the assembly precision of the product but also cause the force concentration part, which will affect the product deployable performance and precision. In the process of mechanical assembly and adjustment, because there is no monitoring measure for precise adjustment of force and position, overshoot and repetition often occur in the assembly process, which seriously reduces the assembly efficiency and prolongs the product development cycle [2]. For large space mechanisms, especially the solar wing, antenna and other parts of the deployable mechanism, the effect of ground gravity is particularly prominent. Therefore, when the components of a large space mechanism are assembled on the ground, it is necessary to use a microgravity assembly device to balance the gravity, weaken its influence on the spacecraft structure and simulate the technical state of these structures in space. At the same time, during assembling a large space mechanism, it is necessary to monitor the assembly condition of key components at all times to ensure the assembly quality.

At present, the commonly used microgravity assembly technique through gravity unloading of space deployable mechanism mainly includes guide rail hanging, balloon hanging and air floating support [3]. Guide rail hanging is suitable for the two-dimensional plane deployment of small and medium-sized mechanism. However, it has some considerable friction and takes up a lot of space [4]. Therefore, the assembly and ground test of large multi-degree-of-freedom space deployable mechanism cannot be satisfied by

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guide rail hanging. Balloon hanging is simple and easy to implement. However, balloons are large and move slow [5]. Therefore, it is only suitable for lightweight and low deployable speed assembly. The air float supporting technology uses the gas pressure to float the object from the air film so that the object can move freely in a certain space. However, it is impossible to precisely adjust the force, torque, and position of the object.

In addition, when carrying out microgravity assembly of the large space mechanism, special tooling was also usually used in the past and the assembly process was mainly conducted by manual operations. Nowadays, flexible and collaborative robots can be used for auxiliary assembly [6]. Therefore, the introduction of a flexible and high-precision collaborative robot can replace the traditional tooling to obtain the force, torque, and position of the components to be assembled of the large space mechanism in real-time and ensure the assembly quality. On the other hand, the traditional assembly process is complex and changeable, which needs to rely heavily on the operation experience of workers [7]. The mixed reality technology is used for assembly assistance and condition monitoring, and the virtual scene is mixed with the real scene. Compared to traditional assembly assistance means, mixed reality technology is more intuitive, easier to understand and can reduce the possibility of errors in the assembly [8]. Therefore, it is of great significance to use mixed reality and collaborative robot technology to visually guide the microgravity assembly of the large space mechanism to improve assembly quality and efficiency.

In human-robot collaborative assembly, robots often need to dynamically change their pre-planned tasks in order to collaborate with operators in a shared workspace [9]. Wang et al.[10] put forward the multi-modal yet symbiotic communication and control methods, it can effectively support the human-robot collaboration. Niki Kousi et al.[11] proposed an augmented reality-based software to assist operators using mobile robots in production systems, improving their versatility and flexibility. Garcia et al. [12] proposed a control interface to introduce human decision-making ability into intelligent manufacturing assembly systems. The interface allows control, coordination, and collaboration with the robot during task execution. Compared with the traditional remote interface, it no longer requires real physical interaction to program the robot and realize remote control. Ong et al. [13] from the national university of Singapore proposed an augmented reality (AR) assisted robot programming system (ARRPS). The system provides a faster and more intuitive robot moving path and task planning than traditional technologies. Their research shows that human-machine collaboration has become the future development trend of intelligent manufacturing. The realization of the interoperability technology between wearable devices and collaboration robots can enable the collaboration robots to have the ability of perception and decision-making, so that they can adapt to more production scenarios, thus increasing the safety of man-machine collaboration and improving the assembly efficiency.

In recent years, many aerospace manufacturers have begun to try to apply mixed reality and collaborative robot technology in the assembly of aerospace products [14]. The traditional manual assembly on-site depends more on the proficiency and technical level of operators. The more difficult the operation is, the higher the requirements for operators are, the greater the possibility of errors. Operators usually need to use written instruction manuals to review the operation process, which not only brings operational inconvenience but also reduces assembly efficiency. Mixed reality and wearable device assisted assembly technology can provide operators with prompt information to guide assembly in real-time by displaying devices. The combination of virtual and real assembly animation enables users to observe the virtual assembly guidance information and the real assembly environment at the same time. The operator assembles according to the instructions of the process, getting rid of the dependence on the manual, liberating the worker's hands, and ensuring the safety of the operation with an open field of vision. To realize the popularization of mixed reality and collaborative robot technology in enterprise production is an important direction of manufacturing development [15,16]. Especially for the assembly of large space deployable mechanism, the assembly process requires high precision, and the assembly and adjustment process is complicated and tedious. Therefore, it is of great significance to use mixed reality and collaborative robot technology to visually guide the microgravity assembly of the large space mechanism to improve assembly quality and efficiency.

In this paper, the second section introduces the architecture of the assisted assembly system. The third section presents the microgravity assembly process based on a collaborative robot and mixed reality. Then Section 4 details human-machine collaboration and assembly condition monitoring based on MR, including human-machine collaboration mode based on MR, interoperability between MR devices and collaborative robot, and assembly condition monitoring based on MR. Section 5 presents the experimental verification scenario and verification scheme. Finally, conclusion and future works are summarized.

2. The architecture of the assisted assembly system

In order to solve the problems existing in the microgravity assembly of the large space mechanism, such as high dependency on workers' experience and proficiency, low assembly efficiency, and quite inconvenience due to paper or screen assisted operation guidance. This research designed a collaborative robot and mixed reality assisted assembly system for microgravity assembly of the large space mechanism. Fig. 1 shows the overall architecture for a collaborative robot and mixed reality assisted assembly system. The purpose of this research is to use mixed reality technology and collaborative robot to visually assist workers in microgravity assembly of the large space deployment mechanism, to help workers quickly and accurately understand assembly requirements in complex environments and monitor assembly condition, so as to improve assembly efficiency and reduce assembly errors.

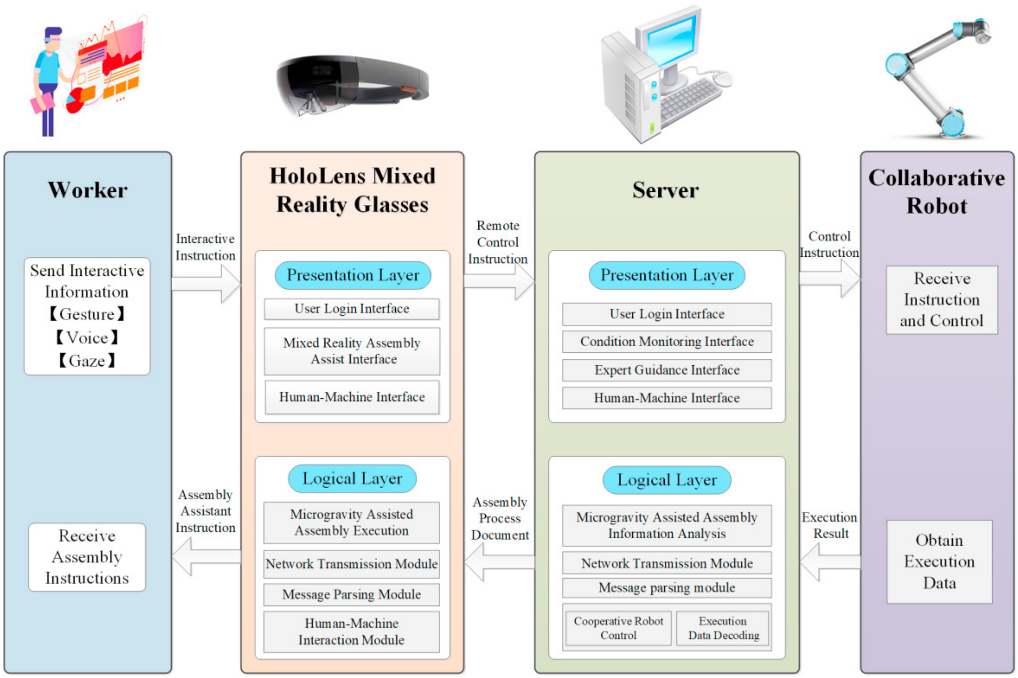


Fig. 1. The overall architecture for collaborative robot and mixed reality assisted assembly system.

In general, the hardware foundation of the proposed system is divided into three parts: Microsoft HoloLens mixed reality glasses, a computer server, and an execution device represented by a collaborative robot. The software foundation is divided into two parts: server-side software with a computer as the platform and mobile software with HoloLens as the platform, which is divided into data processing and data display interaction at the level.

HoloLens can display different forms of assembly guidance information in process assistance files, providing real-time guidance to assembly workers. Workers can interactively send instructions to HoloLens, manipulate the display of guidance information and control the collaborative robot. After receiving the control signal via the server, the collaborative robot can send the execution result back to the operator display on HoloLens via the computer, realizing the interoperation between the wearable device and the collaborative robot.

3. Microgravity assembly process based on a collaborative robot and mixed reality

In order to ensure the perfect working process in the weightless environment of space, it is an essential measure to take the microgravity approach into the assembly of the large space mechanism on the earth. The gravity balance methods commonly used at present include pulley-counterweight, air flotation, balloon suspension, etc. [17]. These methods well simulate the suspension state of the key component (i.e. external truss component) of the mechanism in space, and the effect is good in the ground deployment experiment, but there are still defects in the assembly stage which have more stringent requirements of position accuracy. For example, the traditional gravity balance methods usually limit the degrees of freedom in one direction, which can't realize the positioning in three-dimensional space. The method of microgravity combining collaborative robot and MR proposed in this paper provides a good solution to solve this problem, which can not only achieve the posture adaptive adjustment of components in three-dimension but also simulate the space microgravity environment. The whole process of microgravity assembly for the large space mechanism can be divided into four principal parts. And the detail is shown in Fig 2.

- Posture adjustment process in loops. The posture adjustment is realized by the collaborative robot with the help of the sensors installed in the space mechanism and the end of the robot. The sensors' data includes force and displacement information, and these data are used to optimize the end motion path of the robot to avoid damage to the product during the process. And the laser tracker is used to measure the final coordinates of the key points. And finally, the external truss component will be in the right posture after several loops

- The gravity balance stage. The posture adjustment and gravity balance are separated in the method of this study. After the posture adjustment, the gravity balance process is performed to simulate the suspension state of space, which can be achieved by the six-dimensional force sensor installed at the end of the robot. And the robot works under the force control mode to balance the gravity in the vertical direction. The other directions forces or torque are all close to zero, which may cause the robot end move. As a result, the measurement by laser tracker is necessary after the gravity balance.

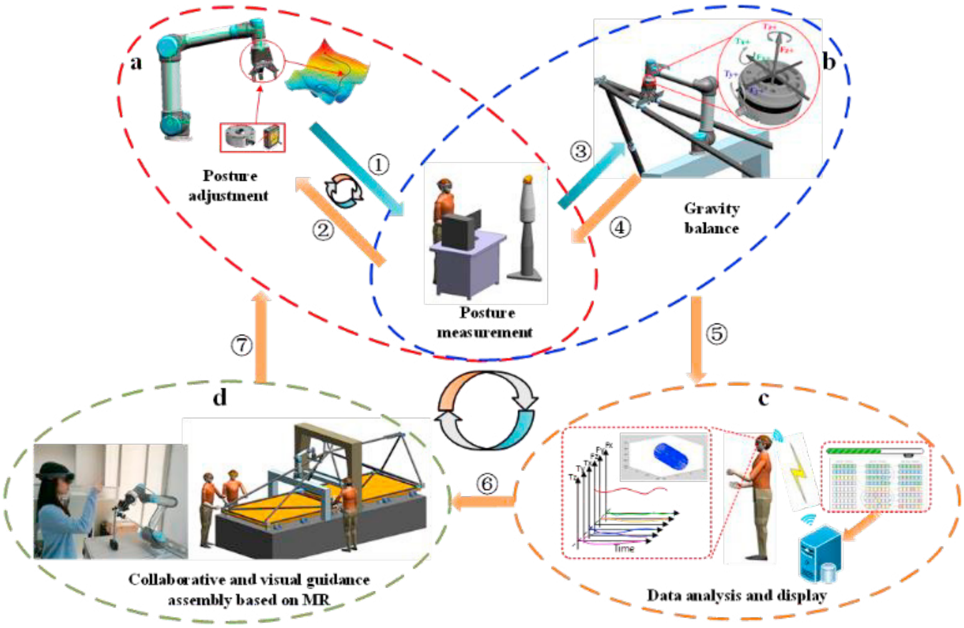


Fig. 2. The workflow of microgravity assembly assisted by robot and MR. (a) The posture adjustment by collaborative robot and laser tracker; (b) The process of Gravity balance by six-dimensional force sensor and laser tracker; (c) Data analysis and display of measurement and monitoring; (d) Collaborative and visual guidance assembly based on MR for the manual assembly and key parts fettling.

- Data analysis and display. The data generated during posture adjustment and gravity balance include force, torque and coordinate information, and they are analyzed by the server to generate the conclusion of the repair parameters of the key parts. And in this stage, the data analysis results will be displayed by the MR in an intuitive way.

- Collaborative and visual guidance based on MR. This method needs sever loops to reach perfect quality. The manual adjustment and key parts fettling is necessary for each loop. The MR glasses help the process of manual adjustment and parts repairment in a collaborative way.

The external truss component of the large space mechanism will be adjusted in an accuracy posture with a gravity balance state after several loops. It has to note that the process of microgravity assembly in this study is time-saving compared with the traditional method because of the posture adjustment, posture measurement, gravity balance, and data analysis are all automatically. And as the key technology of this method, the human-machine collaboration and state-monitoring based on MR can help to improve efficiency and reduce the difficulty of assembly, which is described in detail in the following section.

4. Human-machine collaboration and assembly condition monitoring based on MR

This section is divided into three parts to introduce MR-based human-machine cooperation and assembly condition monitoring. In this research, Microsoft HoloLens, a kind of mixed reality glasses, was used as wearable devices for human-machine collaboration and assembly condition monitoring. Section 4.1 presents the human-machine collaboration flow in the microgravity assembly process. Section 4.2 details the interoperability scheme and key technologies between wearable devices and the collaborative robot. Section 4.3 mainly gives introduces the implementation mode and the main functions of assembly condition monitoring.

4.1. Human-machine collaboration mode based on MR

Visual assembly guidance assisted by mixed reality and wearable devices can use HoloLens to provide operators with prompts to guide assembly in real-time. Assembly workers can rely on assembly instructions provided by wearable devices, such as text, animation, three-dimensional model information, more intuitive understanding of the specific process of product assembly, reducing the assembly wrong operation due to workers understand the error, shortening the time of workers on the analysis of the assembly process documents, and improving the assembly efficiency and worker safety. Fig. 3. shows the human-machine collaboration mode of microgravity assembly. During microgravity assembly, operators wear the HoloLens mixed reality glasses to send measurement instructions. The position, force, and torque of the component to be assembled at the assembly site are measured by laser tracker, six-dimensional force sensor and other measuring and sensing devices, and the data are sent to the HoloLens through the server. After receiving the execution instruction, the collaborative robot performs the microgravity assembly task of adjusts the position, force, and torque of the microgravity external truss component. After the execution, the results are fed back to the HoloLens through the server. According to the feedback information in the HoloLens and the actual scene at the assembly scene, the workers repeatedly adjust the external truss component position, force, and torque until the assembly precision requirements are met.

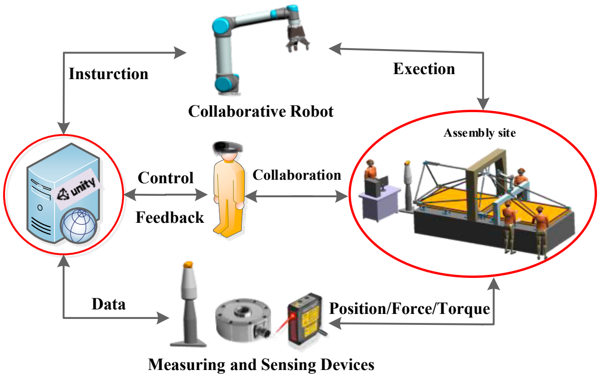


Fig. 3. Human-machine collaboration mode of microgravity assembly

4.2. Interoperability between MR devices and collaborative robot

In the assembly of large space mechanism, the realization of the interoperation technology between MR device and the collaborative robot can enable the collaborative robot to have the perception and decision-making ability, so as to adapt to more production scenarios, thus increasing the safety of human-machine cooperation and improving the assembly efficiency.

Fig. 4 illustrates the interoperation scheme between the MR device and robot. In the interoperation process, the operator sends instructions through voice, gesture, or gaze. The HoloLens displays the current process steps according to the process plan of microgravity assembly. Occlusion of virtual reality, simultaneous localization and mapping (SLAM) and linkage of virtual reality are used to visually display and guide assembly for workers.

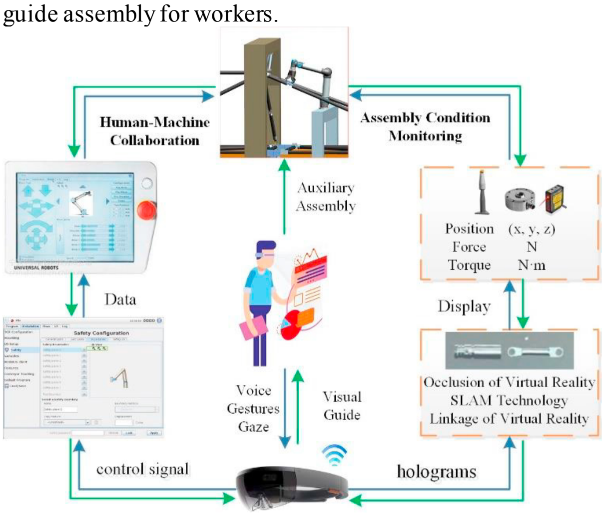


Fig. 4. The MR device and robot interoperability scheme.

The linkage of virtual reality is based on the external physical characteristic of the parts, not the marking points, as reference points. Vuforia was used to scan the characteristic points of parts to determine the properties of parts, and SLAM was used to track and register the current parts, and three-dimensional animation was used to show the assembly operation of the current process and guide workers to assemble. It avoids the disadvantages that the parts must be fixed in a certain spatial position because of the previous mounting mode based on fixed mark points. The linkage of virtual reality can realize flexible installation and adjustment guidance according to the location of parts on the workers' site. The occlusion of virtual reality is to use the depth sensor on HoloLens to collect the depth information in the current field of vision and to compare and judge the spatial position relationship between virtual objects and real objects. Then, occlusion rendering is carried out to make the real object partially occlude the virtual object and enhance the visual reality of mixed reality. In addition, a direction indicator and the assembly path will appear, indicating the assembly path and direction of the current parts and guiding workers to assemble.

According to the monitoring data and the visual display of the assembly process, the workers send control instructions to the collaborative robot through the server to control the movement of the collaborative robot and the position and force of the end gripper of the collaborative robot. After each execution, the collaborative robot will feedback on the execution information to the worker and measure the current value of the components to be assembled. After repeated measurement and adjustment, the position, force, and torque of the component to be assembled are controlled within a certain error range of assembly requirements.

4.3. Assembly condition monitoring based on MR

The realization method of assembly condition monitoring is shown in Fig. 5. Real-time monitoring is achieved through laser tracker, six-dimensional force sensor and other measuring and sensing devices. Data is passed as a message, which is analysed by the server and then passed to HoloLens. Finally, the position coordinates, force, and torque information of the components to be assembled can be displayed at HoloLens glasses. The laser tracker is placed on the assembly site and can measure the three-dimensional position coordinates of the components. The six-dimensional force sensor is installed at the end of the robot and can measure the force and torque of the components. (1) In the beginning, each measurement device and MR device is added into the message transmission environment, and the User Datagram Protocol (UDP) message transmission mechanism is established. (2) The worker sends request instructions to the server through the HoloLens. (3) The server receives the measurement request from the worker. (4) The server sends it to the measuring and sensing device through the measuring module. (5) The measurement device executes the request and feedback information and data. (6) The server shall process the obtained information and data. (7) The server sends the required information to the HoloLens for analysis and display. Repeat the process from (2) to (7) continuously to monitor the assembly condition of components until (8) the end of the assembly task.

In addition, the HoloLens will send workers a warning of danger when a monitoring value exceeds its safe range.

Workers can also view historical data records to analyse and trace original control decisions.

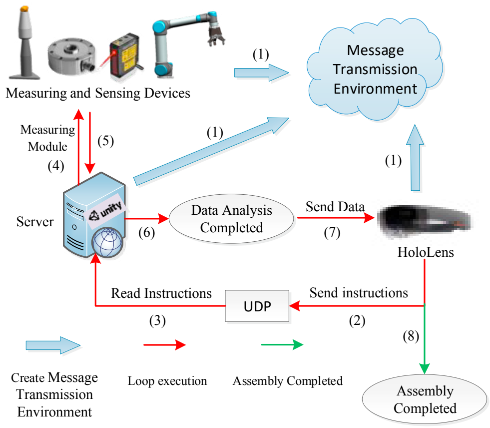


Fig. 5. The realization method of assembly condition monitoring.

5. Experimental verification

In the process of microgravity assembly of the large space mechanism, it is necessary to assemble the external truss component, and precisely adjust the position, force, and torque of the external truss component to ensure that the assembly precision of the external truss component meets the design requirements. In other words, the assembly process requirements of the external truss component require that the coaxial of the two holes of the hinge and the axis of the two holes be parallel to the external axis. The assembly process requires high precision requirements, and assembly and adjustment by traditional manual workers will be complicated and tedious. By using a collaborative robot to assist workers in assembly, the position, force, and torque of the external truss component can be adjusted precisely, and the assembly of the external truss component can be completed quickly. First, the worker sent measurement instructions to MR glasses by voice, gesture or gaze, and measured the theoretical position of the external truss component assembly with a laser tracker. The collaborative robot grabs the external truss component and places it in the theoretical position. Then, the worker sent control instructions through MR glasses to measure the force and torque of the external truss component using the six-dimensional force sensor. The worker sends instructions through MR glasses to the co-robot, which balances the forces and torques of the external truss component by adjusting their position. The worker determined the magnitude and direction of the force and torque being adjusted through the collaborative robot by looking at the values of measurement displayed on the MR glasses. In the process of adjusting the force and torque of the external truss component, the collaborative robot will cause the position movement of the external truss component. The worker again sends the measurement instruction to the MR glasses to control the laser tracker to measure the position of the external truss component. After the actual position of the external truss component is measured by the laser tracker again, the collaborative robot repeatedly adjusts the position of the external truss component to the theoretical position. Workers send instructions through MR glasses to repeatedly measure and adjust the position, force, and torque of the external truss members until the hinge assembly precision meets the space requirements.

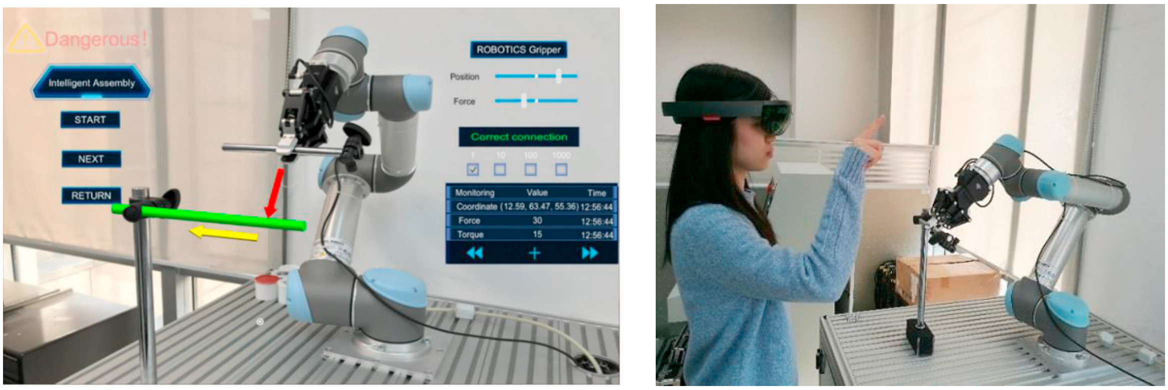
The collaborative robot and mixed reality assisted assembly system has been tested and validated in a laboratory environment and the large space mechanical assembly site. Fig. 6 shows the scene of a functional test and verification of the system using auxiliary assembly function verification samples in the laboratory A worker wearing a HoloLens controls the collaborative robot and monitors the assembly condition in real-time. A rod bar as the mimic space hinge of a large space mechanism is used for testing its microgravity assembly process and operations.

Fig. 6(a) shows the scene in the HoloLens glasses during the assembly process. Intermediate virtual parts are the linkage of virtual and real effects. The icon on the top left is a dangerous warning. The icon will flash and highlight when the monitoring value is beyond the normal range. The operation buttons are at the bottom left. Workers can control the assembly process by clicking start, next step or return. The upper right is the control slider for the position and force of the end gripper of the collaborative robot. Workers can use the slider to control the position and force of the gripper. In the middle of the right is the prompt bar of connection status between the collaborative robot and HoloLens. If the connection is successful, the green 'Correct connection' will be displayed. On the contrary, a red 'Connection error' is displayed if the connection fails. The lower right is the display bar of assembly condition monitoring to display the position, force, and torque of the components to be assembled. The worker can choose the order of magnitude according to the actual value size.

Fig. 6(b) shows the worker wearing the HoloLens mixed reality glasses in the assembly process to operate and adjust the collaborative robot through gestures.

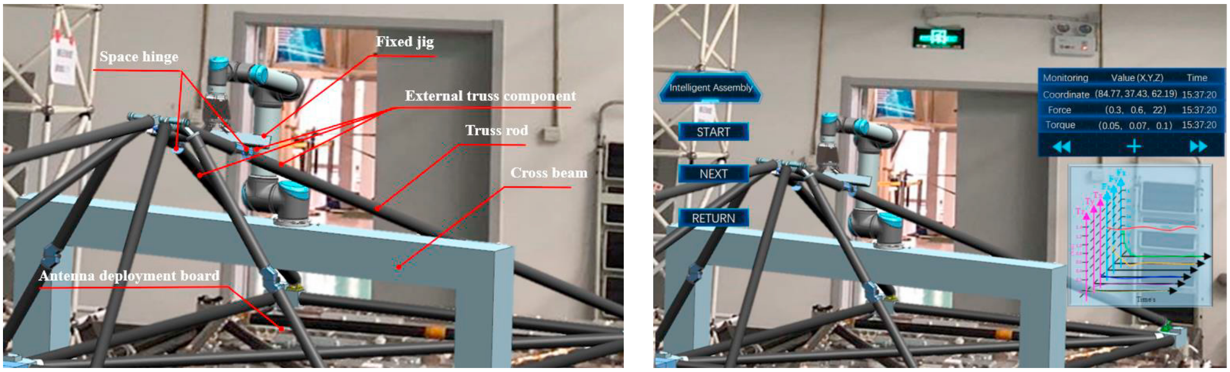
The gravity balance function of the system is validated in the workshop of a large space deployment mechanism. Fig. 7(a) shows the assembly site scenario of the large space mechanism, including an antenna deployable board, a collaborative robot, a cross beam as the support tooling for a robot, a number of truss rods, space hinges and a fixed jig used for keeping the space hinges. The fixed jig is gripped by the collaborative robot, as shown in the middle of Fig. 7(a). The MR interface of gravity balance is shown in Fig.7(b). The most critical information in the gravity balance stage is the value of the six-dimensional force sensor that includes three force and three torque. The value of the sensor is shown in an intuitive means as the lower right corner of Fig.7(b) by the MR. As the coordinates graph shows, the value of the vertical force named Fz is stable at 22N, and the other forces and torques are almost to a vanishing point. The real-time data of the six-dimensional force sensor is displayed in the text box at the top right of Fig.7(b). In addition, the coordinates of the key point of the deployment mechanism are also concerned at the gravity balance stage. The actual value of the coordinates are measured by the laser tracker and displayed on the MR glasses as the top right corner of Fig.7(b).

Traditional microgravity assembly relies heavily on manual work and specialized equipment and tooling, resulting in



(a) (b)

Fig. 6. (a) Display scenario in HoloLens during assembly; (b) Interactive guidance for the assembly process of a rod bar.



(a) (b)

Fig. 7. (a)The assembly site of a large space mechanism; (b)The MR interface of gravity balance in the assembly site.

complex operations, high cost, time-consuming and poor precision. Therefore, it is necessary to incorporate collaborative robots to simulate microgravity state and adjust the position, force, and torque of the external truss component. The microgravity assembly method and the prototype system proposed in this paper have been verified in the field of large space mechanism assembly, and the verification shows that the system is a benefit to improve assembly efficiency and quality. The use of collaborative robot and MR assisted microgravity assembly can not only achieve the gravity unloading but also can achieve precise position adjustment, avoiding the manual repeated adjustment. Taking the verified external truss component assembly as an example, the assembly time is about 30% shorter than the original manual assembly.

6. Conclusion and future works

Intelligent assembly is an important but difficult technology topic in intelligent manufacturing. Collaborative robot and MR devices are used to assist workers in assembly to make assembly more intelligent. This research proposed and designed a collaborative robot and mixed reality assisted assembly system for microgravity assembly of the large space mechanism. Human-machine collaboration and mixed reality are combined to assist worker assembly to meet the requirements of microgravity assembly and assembly condition monitoring during the assembly process of the large space mechanism. The system has been verified in the laboratory environment and assembly site. The key functions and results of the system are promising. Future researches will be focused on the optimization of the data analysis and the mixed reality display functions. For the further development of the presented system, two important functions are needed to be realized. The first one is the collaborative assembly mode where multiple workers with multiple roles are required to working concurrently at a fixed workstation. In such mode, the operation orders and monitoring data will be pushed to the appropriate workers of different roles in real-time to realize efficient collaboration and information sharing. The second is the model lightweight processing which is crucial to improve the user-friendliness of MR applications in the intelligent collaborative assembly of large-scale and complex products. At present, we have made a preliminary verification of the system, and we will do the relevant microgravity calculation model and system optimization in the future.

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