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Supervised Control for Robot-Assisted Surgery Using Augmented Reality

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Abstract: In this paper, we propose an AR-based robotic system that can plan and execute a trajectory based on a 3D medical model and allow the surgeon to supervise the execution of surgical process. In order to achieve image-guided surgery, a hand-eye calibration procedure is developed by using AprilTag to obtain the transformation between the workspace coordinate and the robot coordinate, and perform the image navigation task of the surgical robot to complete a drilling task. A procedure of robot supervised control is proposed to assign or modify the robot trajectory based on AR visualization and 3D model. A specified AR marker is used to project virtual objects in the AR glasses. We developed a robot registration algorithm to match the AR virtual coordinate system and the workspace coordinate system, and convert the planned trajectory into robot trajectory. Experimental results on the lab-built robotic system show that a user can adjust the position and orientation of the insertion point on a bone model, and transmit the trajectory information to the robot for execution. The proposed visualization-based robot navigation method has the potential to enhance the safety of surgical operation.

Keywords: Surgical robot, AR technology, supervised control, robotic surgical navigation

1. INTRODUCTION

In recent years, more and more robot technologies have been developed for medical systems to increase safety and improve quality for surgery. The 3D image navigation and AR technology are promising to provide more intuitive visual experience for surgeons, and effectively improve the quality of surgical operation[1]. There has been a lot of research to study the robot-assisted navigation system. Miao *et al.* [2]developed a high-precision surgical navigation system based on C-Arm. Luo *et al.* [3]proposed a surgical navigation system based on Image-Guided Surgical Toolkit (IGSTK), which can guide a medical robot to accurately implant pedicle screw into the vertebrae.

In the application of robot-assisted surgery, it will involve three coordinate systems: the robot, real environment and virtual environment. Lin *et al.* [4]developed a surgical navigation system for pedicle screw implantation. The system features the transformation between force feedback devices, the virtual environment of the 3D medical model and the robot arm. In the robot-assisted navigation system, registration is required between the robot and the imaging system. Common tracking methods are limited by issues such as the visibility of markers, occlusion problems, or the complexity of registration algorithms. Therefore, Gulhar *et al.* [5] proposed a method to register the robot system to the imaging system by setting landmarks in both systems. This method no longer relies on tracking equipment or X-ray imaging instruments. Amarillo *et al.* [6] developed a new type of robot-assisted surgical system termed RoboTracker consisting of electromechanical tracking devices, which allows the monitoring of the patient's position and orientation throughout the operation without the need to use too much X-rays or conventional optics to improve accuracy.

Augmented Reality (AR) works to overlay and interact with the virtual world on the on-site scene. The AR technology integrates the three-dimensional model and the real environment to evaluate the surgical path and can be directly given to the robot for execution. When the doctor wears an AR glasses, the part of the patient who needs to be operated becomes clear, which improves the efficiency of the operation. During the operation, the 3D image of the patient including the preoperative plan is projected into the field of view and accurately matches the real field of view. Even if the surgeon or patient moves during the operation, the virtual image will accurately overlap with the actual field of view. Liebmann *et al.* [7] developed a navigation method for spinal fusion surgery, including surface-based registration and intuitive holographic navigation. This method was implemented using a commercially available helmet (Microsoft HoloLens). Perkins [8] developed a Mixed Reality (MR) system that can use Microsoft HoloLens to project 3D holograms of MRI images onto patients. Relying on preoperative images cannot resolve registration errors or intraoperative anatomical changes, and the navigation system cannot provide surgeons with mechanical assistance. Kim *et al.* [9] proposed a system architecture that integrates real-time image feedback into a remote robot system that can provide guidance through virtual devices.

Orthopedic surgery requires accuracy and safety, but there is no standard guideline that clearly defines the character of AR visualization, surgical robots, and doctors. Thus, an integrated system demand urgent attention to include both the robot navigation system and the AR visualization system. Further, in actual situations, unexpected situation may occur during operation. In the robot motion planning system, few ideas have been discussed about the doctor intervention monitoring[10]. Although there are many studies that use AR technology to optimize the navigation field of view, which is very helpful for understanding medical information during surgery, these studies still focus on manual manipulation.

In this paper we propose a novel supervised robot-assisted navigation system for pedicle screw implantation. A Lab-made robot is used to establish a robotic platform, which can plan the trajectory for the surgical task of the implant. In the suggested architecture, tasks are performed by robot rather than by doctors. In order for a surgeon to obtain more adequate information, it is necessary to update the robot pose in real time and project medical model information so that the surgeon can re-plan, which means real-time supervision. For a more intuitive adjustment, we propose a procedure that the adjustment of the surgical trajectory be performed on the AR interface.

2. PROPOSED SYSTEM ARCHITECTURE

The proposed system architecture of the AR supervised navigation system is shown in Fig. 1. The AR technology is applied to visualize surgical trajectories and medical models in a real environment. Based on this information, the doctor can adjust the position and orientation of the surgical instrument and confirm whether it is suitable for the current situation, and then decide whether to further engage in the robot arm control. The proposed system architecture consists of three parts. The first part is the surgical robot navigation system. The second part is the AR visualization system. The third part is the real-time supervised module, which integrates the first two parts together. The design includes the transformation between the robot arm system coordinate and the virtual AR environment coordinates, and the UI interface for artificially adjusting the trajectory. Therefore, the path planning in the AR visualization environment can be converted into the trajectory of the robot, and the surgical task planning performed by the robot arm can be adjusted to achieve real-time supervised behavior.

3. ROBOT NAVIGATION SYSTEM

We take the case of spinal fusion surgery as a design target, in which pedicle screws are implanted into the patient. We simplify the surgical task to a defined insertion point and a straight-line path to reach the target point, as shown in Fig. 2. The red and blue trajectories have the same insertion point, but due to the different orientations, different trajectories will be formed. The key to plan the trajectory is to determine the insertion point including the position, orientation and length of the implantation. Before surgery, a preoperative trajectory will be planned based on the bone model. Because the planned path will be a linear movement with a fixed orientation. The starting point of the straight line is the insertion point, and the end point is the final placement of the pedicle screws. And in the process of linear movement through these two points, it is necessary to keep the orientation unchanged. The pre-planned starting and ending points can be found by using the model. The location of two points in the simulation system is obtained through image registration. We adopted the hand-eye calibration method in [11] to obtain the transformation between the camera and the robot base. With the transformation, we obtained the transformation of the robot and bone model by recognizing the AprilTag on the bone model through the camera. In this way, the pre-operative trajectory planned on the bone model can be transferred to the robot execution trajectory. Specify the starting point and ending point in the robot motion-computing system to plan a straight line trajectory. First, the Cartesian coordinate points are divided into equal distances from two points, and then the position information in the Cartesian space is converted into configuration space information through inverse kinematics. Thus, the linear trajectory of the robot system can be obtained.

4. AR VISUALIZATION

AR technology has made great progress in medical area. However, one of the most difficult parts is to overlay the virtual image to the surgeon's vision in real time and accurately align with the objects in the real world. In this design, a simulation environment will be

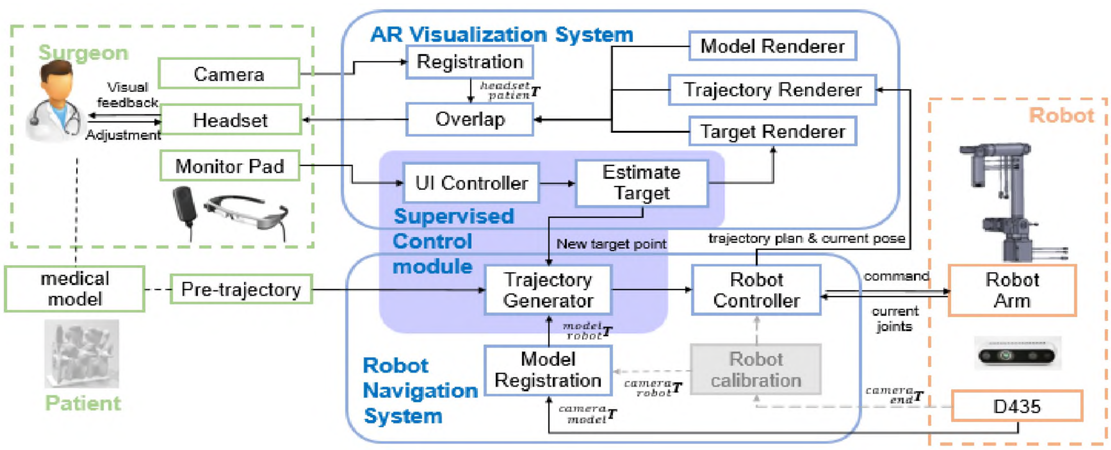


Fig. 1. System architecture of the proposed AR-based robot navigation supervised system

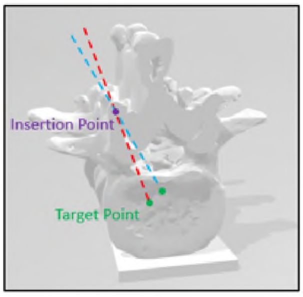


Fig. 2 Two trajectory on the bone model

built to contain medical image model and robot arm trajectory. The medical image model will be registered with the real model to obtain the relative relationship between the model's reality and virtual. There are two types of robotic trajectories, one is the preoperative trajectory drawn according to the image model, and the other is the trajectory that the robotic arm is expected to perform. This part will be instantly communicated with the robot arm control system. Further, it will include a graphical interface for the user to adjust the trajectory.

In order to visualize all information, it is necessary to find the relationship between the virtual and real world coordinate systems. We use the camera to recognize the AR marker in the real environment and compare it with the object in the virtual coordinates to obtain the transformation between the two world coordinates. The AR marker is composed of multiple geometric lines and help for the image recognition effect. As shown in Fig. 3, the camera on the head-mounted device can recognize the AR marker in the environment. Using image recognition[13] to analyze the deformation of the marker on the screen, the relationship between the camera coordinate system (Xc, Yc, Zc) and the logo coordinate system (Xm, Ym, Zm) can be obtained. The image of the user's field of view is the result of the camera screen after superimposing the virtual object. With the projected transformation between the AR marker and the head-mounted device, the position (x, y) of the virtual object on the screen view can be calculated accordingly.

There will be three virtual objects in the user's field of vision, the patient's 3D medical bone model, the planning trajectory of the robot, and the trajectory adjusted by the doctor. The medical bone model [15] is converted from CT images of real lumbar vertebrae and is used to plan and simulate surgical tasks. In the virtual coordinate system, the origin of the coordinate system is based on the AR marker. Trajectories and bone model have coordinate points in this coordinate system. Using the projected transformation mentioned above, these virtual objects can be projected into the user's field of vision. We exploit BT300 as the AR device for visualization, and use Unity to program and implement the AR functions in the android system.

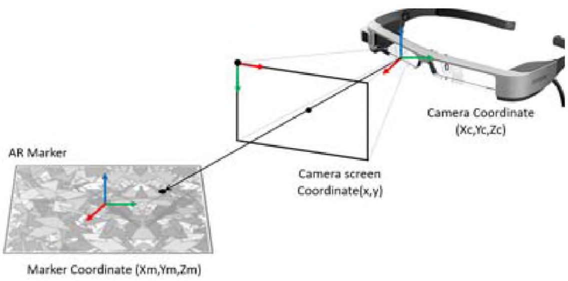


Fig. 3 marker recognition and virtual object

5. SUPERVISED CONTROL SCHEME

The working of the real-time supervised module is to allow doctors to change the trajectory on the AR interface in specific situations. The way to achieve real-time supervising is to use the UI interface to adjust the orientation and position of the drilling point, and the trajectory will be modified in the AR environment in the same time. This module will pass the information to the robot for execution. Since the operating systems of the robot and the AR glasses are different, communication between the two must be established to transfer the adjustment information on the AR side to the robot side. As shown in Fig. 4, system is divided into two blocks, one is system communication, so that different operating systems can transmit information. The other is coordinate registration. Since the coordinate systems of the two systems are different, the trajectory specified on the UI interface needs to be converted into the robot coordinate system.

In order to achieve system communication, the two systems are connected to the same domain. After that, the Android terminal converts the information to be sent into a topic form that can be received by the ROS system, and uses the websocket communication protocol to send the information package[14]. In this way, position and orientation information can be transmitted to the arm for execution.

The purpose of coordinate registration is to find the transformation between the UI interface of the virtual coordinate system (VCS) and the robot base coordinate system (RBCS). The x, y, z axes of the coordinate systems are shown in red, green and blue colors in Fig. 5. The RBCS located at the robot base. The Tool center Point (TCP) at the end of the tool is the origin of the Tool coordinate system (TCS). The origin of the World

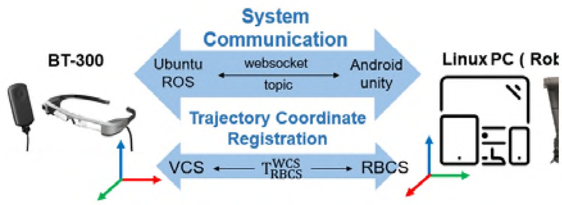


Fig. 4 Schematic diagram of communication

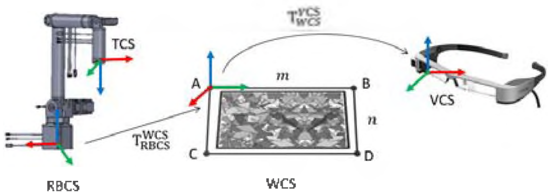


Fig. 5 Schematic diagram of coordinate registration

Coordinate System (WCS) is located at the corner of a given workspace whose length and width are m and n, respectively. The VCS is a coordinate system representing a virtual simulation platform, which contains defined virtual AR markers. The origin of VCS is on the AR marker, so in reality the placement of the marker can get the corresponding origin of VCS. In practical applications, in order for the trajectory in the VCS to be executed by the robot, it is necessary to determining the position and orientation of the RBCS to the VCS represented by $\boldsymbol{T}_{RBCS}^{VCS}$. The transformation WCS to VCS represented by T_{WCS}^{VCS} is already known in the VCS. As long as the WCS to the RBCS is obtained, the RBCS to the VCS can be obtained relatively:

$$\boldsymbol{T}_{RBCS}^{VCS} = \boldsymbol{T}_{RBCS}^{WCS}\boldsymbol{T}_{WCS}^{VCS} \quad (1)$$

Given a rectangular workspace, its length and width are m and n respectively, and the point on the upper left corner is the origin of the WCS. Four-point coordinates of the WCS can be obtained. The transformation of the TCS in the RBCS represented by T_{RBCS}^{TCS} is already known through the Computer-Aided Design (CAD) model of the robot and the tool. $\boldsymbol{T}_{RBCS}^{TCS}$ represents the transformation of the TCP to the RBCS when the tool end of the robot reached the corners of the workspace. Four-point coordinates of the RBCS can be obtained, such that

$$S_w = \{P_W^i\}, S_R = \{P_R^i\}, \quad \text{for i =1,2,3,4} \quad (2)$$

where S_w andS_R are the coordinates sets in the two coordinates systems RBCS and WCS respectively. **P** is defined as,

$$\mathbf{P} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \quad (4)$$

First, find the displacement of the origin of the two coordinate systems, which can obtained from the coordinate of P_R^1 in the RBCS,

$$\boldsymbol{P}_R^1 = \begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} \quad (5)$$

and the transformation is

$$\boldsymbol{T}_1 = \begin{bmatrix} 1 & 0 & 0 & X_A \\ 0 & 1 & 0 & Y_A \\ 0 & 0 & 1 & Z_A \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

where $\boldsymbol{T}_1$ is the displacement of the two coordinate systems RBCS and WCS. The point set of the RBCS will get new position after displacement, as shown in Fig. 6 Since the specified workspace and the robot are placed on the same plane, the Z-axis directions of the two coordinate systems are the same. Thus, the coordinate

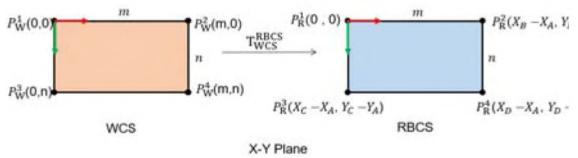


Fig. 6 Schematic diagram of coordinate registration

sets of the two coordinates systems will be on the same plane. Using the Z axis as the rotation axis, rotate θ_z degrees to make the points coincide,

$$\boldsymbol{T}_2 = \begin{bmatrix} \cos\theta_z & -sin\theta_z & 0 & 0 \\ sin\theta_z & cos\theta_z & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

From the above equations, the transformation can be determined, such that

$$\boldsymbol{T}_{WCS}^{RBCS} = \boldsymbol{T}_2\boldsymbol{T}_1 \quad (8)$$

In the previous hand-eye calibration, the relationship between the RBCS and the AprilTag of the workspace can be obtained. In the visualization system, the specified AR marker is used as the reference point for trajectory planning. The marker is placed in the workspace. By calculating the position of the marker in the workspace, the relationship between the RBCS and the VCS can be obtained. The placement trajectory can be simplified into two spatial transformation matrices of the insertion point and the ending point with respect to the marker. When the user is not satisfied with the two points pre-planned by the visualization system, he can readjust the trajectory, and then the system calculates a new trajectory for the robot to execute.

6. EXPERIMAENTAL RESULTS

An experimental surgical robot and spinal cord model have been setup in the lab to realize the proposed system. This system uses a laboratory-made robot arm. We use the MoveIt platform to build a motion-computing system, and use Trac_IK as kinematics calculation tool[16]. Fig. 7 shows the configuration of the experiment setup. The width of the operating table bed is about 70 cm, so the distance between the robot and the camera Real Sense D435 is about 70 cm. And set a workspace between the two, as the position of the affected part, which means the working area of the robot to perform the surgical task.

The experimental results will first verify the robot control and navigation algorithm. Using AprilTag as the insertion point of the preoperative trajectory plan to verify the execution effect of the arm performing surgical tasks. The next experiment is to determine the insertion point on the visualization system side. At this time, the virtual bone model and the real environment are both in the field of view, and the robot can successfully execute the determined trajectory plan. Finally, verify the real-time supervised control. When it is detected that the robot is performing on an inappropriate trajectory, the UI

Fig. 7 Experimental setup

interface can be adjusted through the AR visualization system to change the surgical trajectory plan.

6.1 Experimental results of robot navigation control

This experiment is to verify the functions of the robot navigation system, including robot control, kinematics, and transformation between the WCS and the RBCS. When receiving the trajectory plan, it can successfully perform the path. Here, a trajectory model was created by 3D printing. It contains a hollow cylinder as the path of the entire trajectory, the outer diameter of the circle is 12m, the inner diameter is 9mm, and the upper circular hole is used as the trajectory drilling point. The target point is located at the entrance of the round hole 30mm. The model also designed a flat surface to attach AprilTag. Use Realsense D435 camera to detect AprilTag, which is used to locate the location of this model trajectory. The transformation insertion point to the AprilTag represented by $\boldsymbol{T}_{insertion}^{Apriltag}$, $\boldsymbol{T}_{insertion}^{Apriltag}$ is defined as,

$$\boldsymbol{T}_{insertion}^{Apriltag} = \begin{bmatrix} 1 & 0 & 0 & 0.001 \\ 0 & 0 & -1 & 0.077 \\ 0 & 1 & 0 & -0.043 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (9)$$

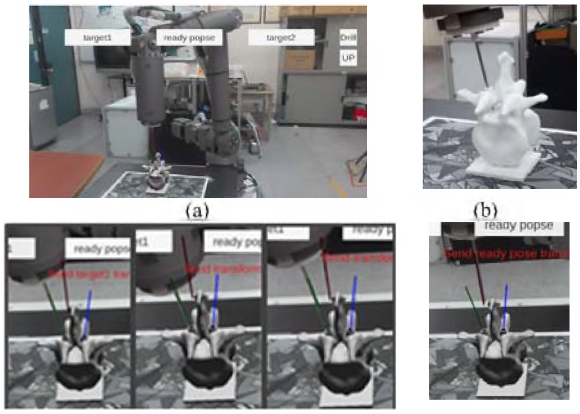
The trajectory model is randomly placed in three different positions in the workspace. By detecting AprilTag and related transformation, trajectory planning can be obtained. Then verify performance of the robot. Record the absolute encoder value of each joints motor of the robot at a frequency of 10 Hz. Use forward kinematics to calculate the robot pose and compare it with the planned trajectory. The results show that the error is about 0.75mm, Table 1.

6.2 Experiment on AR-based Robot Control

This experiment verifies the communication between the android platform of the visualization system and the ROS platform of the robot system through two different trajectories. In addition, virtual objects can be projected in real time in the user's field of view. As shown in Fig.8(a), the user interface (UI) can be used to control the robot with the expected execution trajectory. There are three buttons on the top. Target1, ready pose and Target2 represent the blue, red and green trajectories on the bone from left to right. By clicking the button, the trajectory information will be sent to the ROS system by the visualization system, and then converted into configuration space information through the kinematics and then handed over to the robot for execution. The entire trajectory includes reaching the insertion point, linear trajectory of implantation and returning to the insertion point.

Table 1 Position error of robot navigation control

trajectory	$Error_x$(mm)	$Error_y$(mm)	$Error_z$(mm)	Error(mm)
Seq1-1	0.4495	0.5791	0.9263	0.7448
Seq1-2	0.4451	0.5002	1.2882	0.6543
Seq2-1	0.5280	0.4719	0.9741	0.7698
Seq2-2	0.3589	0.8044	1.3906	0.7013
Seq3-1	0.4573	0.6483	0.8642	0.7564
Seq3-2	0.5138	0.4687	1.4644	0.7699



(c) (d)

Fig. 8. Experimental results of AR-supervised robot trajectory control. (a) user interface. (b) real world (c) insertion of target1(d) return to ready pose

6.3 Experimental results of AR-supervised robot control

The purpose of this experiment is to verify that the proposed supervised system can change the trajectory planning during the operation in time. Before the operation starts, there will be a set of planned trajectories. However, during the operation, the trajectory may need to be adjusted due to changes in the situation. We use AR technology to provide an intuitive 3D visual environment with medical information to doctors. In this way, as the doctor wears an AR device, the bone model, preoperative planning and arm information can be presented in front of the eye. Before robot starts to execute, if the user is not satisfied with the pre-planned trajectory of the insertion point, he/she can adjust the orientation and position of the trajectory through the UI interface. For the way of adjusting the trajectory of the robot, the proposed coordinate method can be used to combine the robot system and the virtual system on the AR device. After this, the adjustment of the arm trajectory can be realized on the virtual system, instead of being executed in the arm system. In order to realize the error between the planned position of the virtual system and the actual execution position, we set a few position points on the virtual system and let the robot execute to this position. The error of the position between the AR system and the Robot is [0.0126, 0.0596, 0.0315] mm, and the error of orientation is [0.00450.00190.0084] degree.

In this experiment, as shown in Fig. 9(a), the center of the screen is the result of the superposition of the real environment and the virtual object. The upper right block is the interface for adjusting the insertion point, which is achieved by adjusting its position and orientation. And in the form of buttons to provide users with control of the process, including ready position, preoperative trajectory execution, determine the orientation of the insertion point and implant trajectory. First, according to the planned trajectory before the operation, it will be displayed in the view as a blue cylinder virtual object, and the robot will be executed to the position, as shown in Fig. 9(b). Due to an improper insertion point, the user adjusted the orientation and position of the trajectory by using the UI.

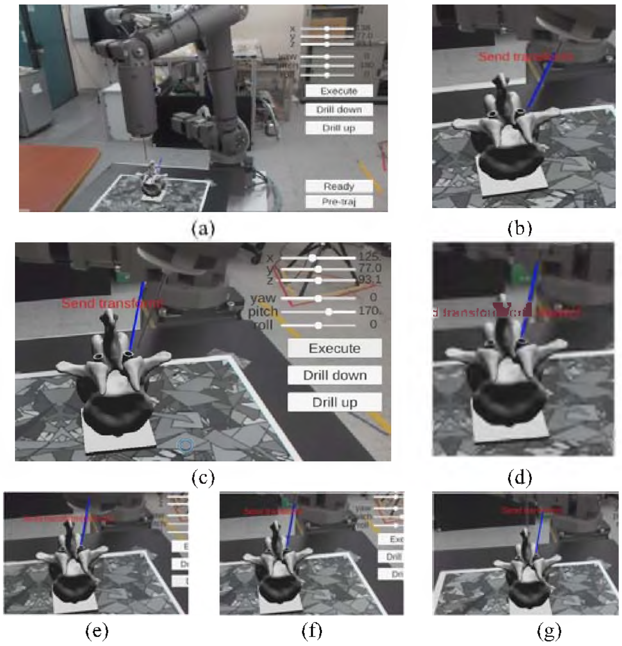


Fig.9. Experimental results of supervised system in BT300 view. (a) user interface. (b) pre-plan trajectory (c) Adjustment new plan (d) at new insertion (e)-(f) execute new plan (g) return to ready pose

The updated trajectory is shown in Fig.9(c).The blue cylinder at this time is the updated trajectory virtual object. Fig. 9(d) is the result of the robot performing an updated insertion point. At this time, the user can decide whether to repeat the previous step again for adjustment according to the result. In Fig. 9 (e)-(f), the entire implantation trajectory is executed according to the adjusted new insertion point. Finally, return to the ready position and wait for the next action.

7. CONCLUSIONS AND FUTUREWORK

In this paper, a supervised control system that combines robot navigation and augmented reality technology is proposed for robotic-assisted pedicle screw implantation. The AR technology is used to establish a visualization system, which can project the 3D bone model and surgical trajectory on the BT-300 AR glasses in real time, and can be used to adjust the robot trajectory on the visualization system through the UI interface. Experimental results on the Lab-built robotic system show that a user can adjust the position and orientation of the insertion point when an improper planned trajectory is found, and transmit the information to the robot for execution. It has been demonstrated for an orthopedic implant surgery that the proposed system completed the simulated implant surgery task with accuracy 0.75mm. In the future we want to enhance the 3D modeling and AR handling to provide more perspectives of the model in UI, so that the surgeon has more information to evaluate the robot trajectory.

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