Tele-operation and Simulation for a New Surgical Robot Design

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ABSTRACT

Femur fracture is a frequently occurred injury and usually treated by surgeries. However, the treatment of femur fracture exhibits many problems such as excessive radiation exposure to both surgeons and patients and mal-alignment in reduction. In order to overcome these problems, robot-assisted reduction surgery has been researched in recent years. One hybrid robot is introduced in this paper for femur fracture reduction. In order to train the surgeon for pre-operative planning or for intra-operative manipulation, we developed a tele-operation and simulation system for the newly developed hybrid robot. In this system, we construct the virtual hybrid robot by V-Realm Builder 2.0 based on VRML language, use MATLAB Simulink and the virtual reality toolbox to build the simulation model, and tele-operation of the virtual hybrid robot is implemented using the Phantom haptic interface. The virtual system presented in this paper creates a realistic environment for demonstration and provides facilities for good quality rendering. The tele-operation system shows that it is convenient and powerful in defining a 3D path. The approach utilized in this paper can also be used to study other types of robot.

Keywords: kinematics, robot simulation, virtual reality, tele-operation.
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1 INTRODUCTION

Femur fracture is a frequent injury [1], however, treatment of femur fracture involves many problems such as large amount of radiation exposure to patient and operating staffs and mal-alignment of bone fragments inducing many complications including but not limited to leg-length discrepancy, angular deformity and compartment syndrome [2]. In order to overcome these problems, robot-assisted reduction surgery has been proposed in recent years [3-7].

Traditional robot development, where experiment proceeds after robot design is completed and hardware is implemented, is relatively time consuming and costly compared to the technology integrated by robot design and virtual reality technologies, furthermore, the hardware implementation of robotics system is very complex and requires multidisciplinary knowledge such as mechanical design, electronics development and control system [8]. Practically the quality and the possibilities of faithful simulations continuously increase with the rapid development of computational power of current computers [9-10]. Current virtual reality technologies could create a friendly and ease-to-use environment for demonstration and provide facilities for good quality rendering [11-12], therefore, exploiting virtual reality based robot simulation instead of physical robot system fabrication seems more practical and useful in many situations, for example, where the robot is not completed immediately or hardware implementation is very expensive for primary stage of robot development [13-15]. In this paper, the robotic system for femur fracture reduction consists of a surgical robot, a robot controller, a fluoroscopy device and a PC computer.

Robots can perform many surgical operations, such as position and reposition surgical tools with great accuracy, applying precisely calibrated and controlled forces, reducing the physiologic tremor of human hands and scaling the magnitudes of forces and motions [16]. Various robots have been developed for femur fracture reduction surgeries and generally are classified into two architectures, serial robot and parallel robot [17]. Most of the serial surgical robots are modified from the industry articulated robot arms, they have the advantages of large workspace, high dexterity and maneuverability, but their disadvantages are obvious. The enormous workspace leads to safety problems such as collision between the robot and the operating environment (medical equipment or medical personnel). The accumulated errors of the links lead to the low position accuracy. Moreover, the larger size and high power consumption of the robot results in its high costs [18]. Thus, serial robot is inappropriate for tasks requiring either the manipulation of heavy loads or a good positioning accuracy. Parallel robots using the stewart platform have high payload to weight ratio, high stiffness and position accuracy. The major drawback of parallel robots is limited workspace [17]. In our project, we are required to develop a compact robot with high payload, good position accuracy and relative large workspace, especially for the angular rotation. So, to balance the position accuracy and workspace, a hybrid robot has been proposed and the 3D assembled model is shown in Fig. 1(a). A complete prototype of the proposed system is shown in Fig. 1(b) and the virtual robotic surgical environment is shown in Fig. 1(c).

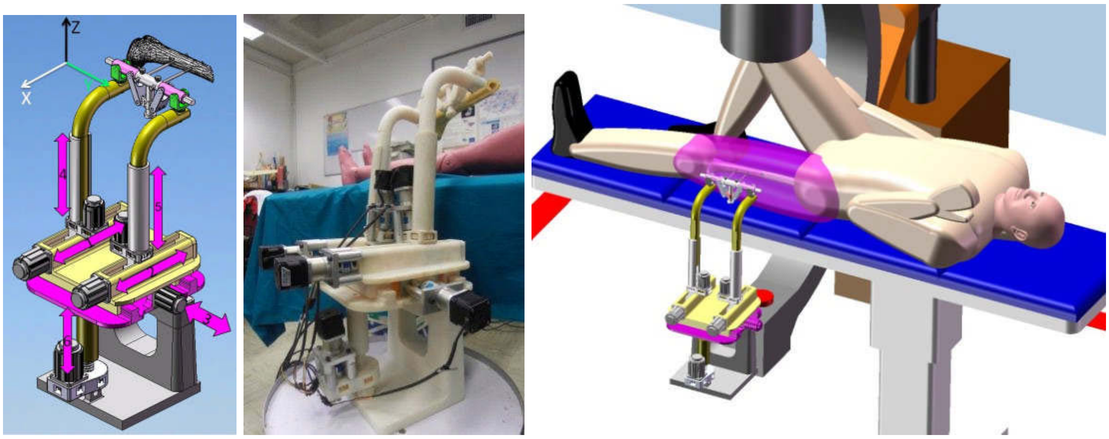

Fig. 1: Surgical robot: (a) 3D robot design, (b) the complete prototype, (c) the virtual environment.

The simulation environment is built using V-Realm Builder 2.0 based on Virtual Reality Modeling Language (VRML) and MATLAB Simulink with virtual reality toolbox. The virtual reality toolbox allows the connection of a virtual world defined with VRML to MATLAB Simulink programs, which makes it simple to control the virtual world by using functions and methods defined in MATLAB Simulink [19-20]. There are some validations of accuracy and practicability of the simulator built using MATLAB Simulink with Virtual Reality Toolbox. Belda presented a method by using MATLAB-Simulink environment for real-time simulation and 3D visualization in controlling redundant parallel robots, which demonstrated good feasibility of implementation under support of virtual reality toolbox [21]. Stan et al reported a virtual reality interface through virtual reality toolbox in MATLAB for the control of one parallel robot with three degrees of freedom [22]. The proposed virtual reality interface was demonstrated to facilitate visualizing motion of mechanical system in 3D virtual space. Ge et al presented 3D visualization of a mobile robot by the virtual reality toolbox. The virtual model is demonstrated to represent dynamic properties of real robot accurately and it could help to test optimization methods of controlling and designing a mobile robot [23]. In this paper, we utilize MATLAB Simulink with virtual reality toolbox to build a virtual environment for robot assisted femur fracture reduction. Then the virtual robot model is controlled and manipulated by a haptic interface. Motion control of the robotic system for femur fracture reduction is simulated in the virtual environment built by virtual reality toolbox. The inverse kinematics of the robot is presented. In the virtual reality environment developed by VRML and MATLAB Simulink, motion patterns of the end-effector are demonstrated to test the accuracy of the inverse kinematics. With the virtual environment, we can perform virtual tele-operation using the haptic interface by linking the Tool Center Point (TCP) of the robot model to the Haptic Interface Point (HIP), details of virtual tele-operation will be presented in section 3.

2 METHODS

2.1 The Surgical Robot

Fig. 1 shows the 3D model, prototype and the virtual environment of the robot system. The dimension of the robot is 200*250*450mm. It consists of six independent linear actuators. The end-effector is supported by two parallel L-shape tubes, so its stiffness is expected to be higher than that of a serial robot arm. The proposed robot inherits advantages of parallel robots and serial robots which are good accuracy, large workspace and free of singularity. The end-effector has two pins screwed to one bone fragment so that the fragment can be controlled to complete the realigning motion. From Fig. 1(a), linear actuators 3-1-4 form one Cartesian coordinate and linear actuators 3-2-5 form another Cartesian coordinate. If the actuators 1# and 2# are moved synchronously or the actuators 4# and 5# are moved synchronously, together with the movement of the actuator 3#, the position of end-effector can be adjusted. If the actuators 1# and 2# are moved asynchronously or the actuators 4# and 5# are moved asynchronously, the orientation of the end-effector could be adjusted. Motion of all the actuators are linear and all the rotational movement of the end-effector is obtained by the linear movement of relevant actuator(s), therefore its movement is smoother and appropriate for the very low speed femur bone fracture reduction procedure. During the process of femur fracture reduction, the proximal fragment is fixed in its position and the distal fragment is fixed on the end-effector and moved to its correct anatomic position.

2.2 Kinematics

The pose of the robot end-effector is defined as $(\mathrm{p}_x, \mathrm{p}_y, \mathrm{p}_z, \gamma, \alpha, \beta)$, where $(\mathrm{p}_x, \mathrm{p}_y, \mathrm{p}_z)$ is the position of the TCP, and (γ, α, β) is the orientation of the end-effector defined by the X-Z-Y Euler angels.

The forward and inverse kinematics of the proposed robot could be found in [17].

For the forward kinematics, by calculating out the forward transformation matrix $T_{FK}()$, we obtain the pose of the end-effector as,

$$(\mathrm{p}_x, \mathrm{p}_y, \mathrm{p}_z, \gamma, \alpha, \beta) = T_{FK}(q) \tag{2.1}$$

Where $q = (d_1, d_2, d_3, d_4, d_5, d_6)$ is the displacement of actuators 1-6.

For the inverse kinematics, given the pose of the end-effector $(\mathrm{p}_x, \mathrm{p}_y, \mathrm{p}_z, \gamma, \alpha, \beta)$, we can calculate the displacement of the actuators using the inverse kinematics. As the hybrid robot characterizes the Cartesian coordinate robot, we first rotate the end-effector by a series rotation about Y-axis, Z-axis and X-axis, to make its orientation parallel to the base orientation, we calculate out the movement of the actuators for the relative rotation. And then the robot can be treated as the Cartesian coordinate robot, we translate the end-effector back to its initial position and calculate out the displacement of the actuators for the relative translation. By sum up the relative displacement of the actuators for the rotation and translation, we obtain the inverse kinematics as,

$$q = T_{IK}(p_x, p_y, p_z, \gamma, \alpha, \beta) \tag{2.2}$$

Where $T_{IK}()$ is the inverse kinematics transformation matrix, details of the deduction of Eqn. (2.1) and (2.2) could be found in [17].

2.3 Virtual Reality Modeling

2.3.1 3D Model of the Robot

The 3D assembly model of the robot is developed in the program V-Realm Builder 2.0 based on VRML language as shown in Fig. 2. Properties of each element consisting of the virtual model, such as position, shape and color, are defined in the program. Robot modeling is based on the hierarchy design methodology, which means that movement of driven element is correlated with the movement of driving element. Therefore, it is convenient to control movement of elements and makes complex motion control simple. The hierarchy scheme of the robot is shown as Fig. 3.

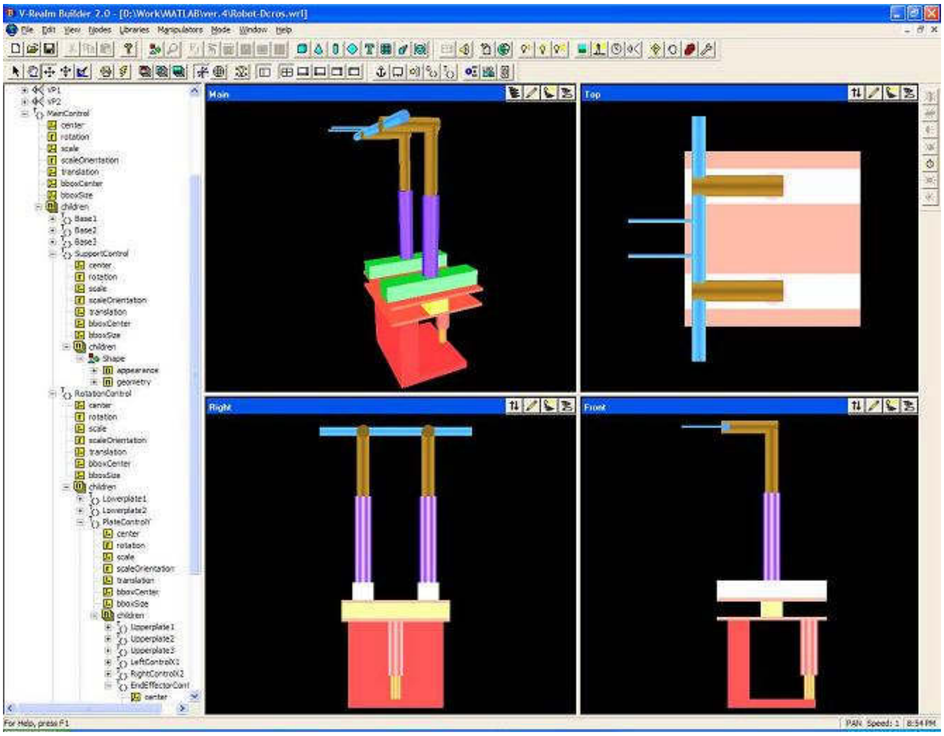

Fig. 2: Robot 3D model created with V-Realm Builder 2.0.

As the hybrid robot consists of the lower platform (The L-shape foundation and actuator 6#) and the upper platform (actuators 1-5), we first construct the robot model with the L-shape foundation and the lower sleeve (actuator 6#). The lower platform serves as the tilting joint about Y-axis. And then we construct the upper platform. The lower base (actuator 3#) serves as the translation joint along Y-axis. Then we construct actuators 1#, 4#, 2#, 5# and finally the end-effector.

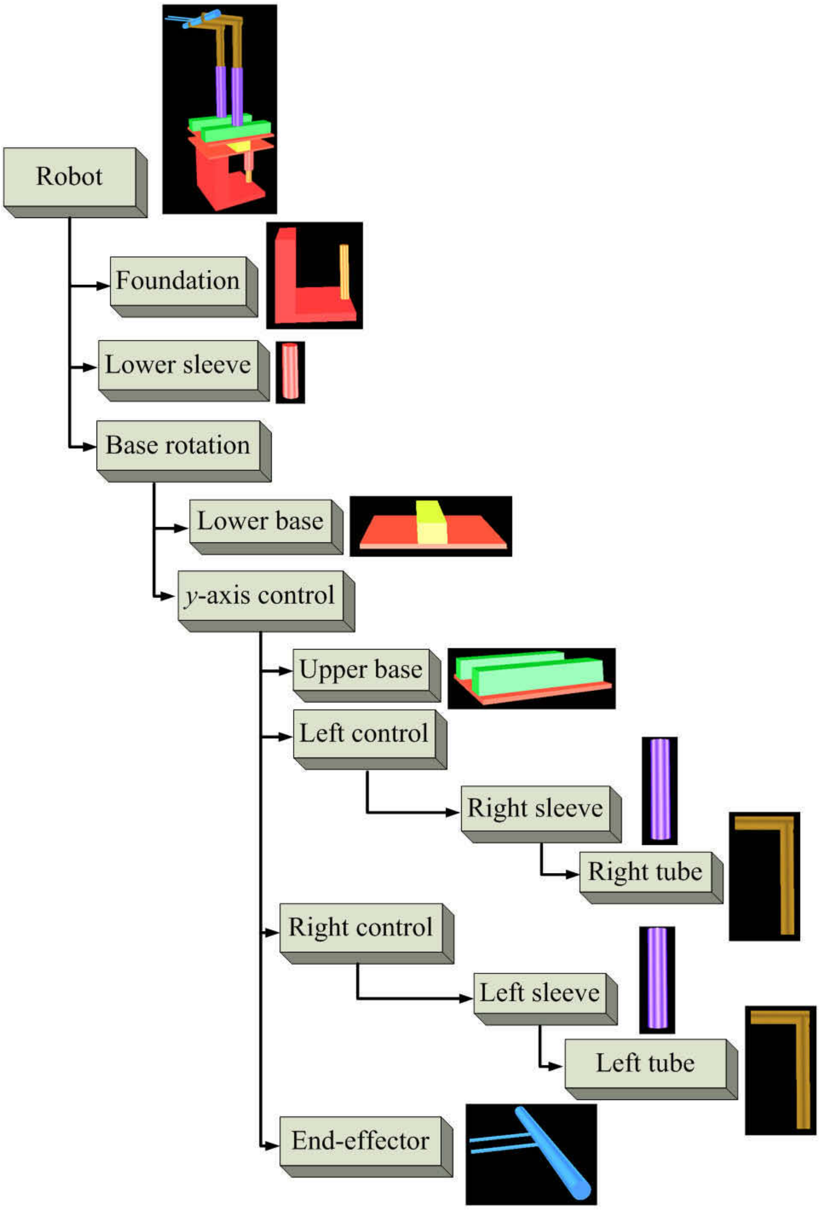

Fig. 3: Hierarchic scheme of the robot.

After construction of each element and assembling them in virtual environment, the ports of the virtual model should be defined to connect the virtual environment and Simulink models, which are used to control the movement of elements such as changing the position or rotating elements around the setup axis.

2.3.2 Model Control

Model control is implemented in MATLAB Simulink program. Movement of all elements of the robot should be coordinated in harmony for achieving the motion of robot, although movements of some elements are integrated together by hierarchic design. For example, in the hierarchic design shown in Fig. 3, movement of the right sleeve is correlated with the movement of right tube, which means that the element of the right tube could be driven correspondingly if the element of the right sleeve is moved. However, the element of end-effector cannot be driven correspondingly no matter how the element of right sleeve is moved, since the element of end-effector is not sub-node of the element of right sleeve. Therefore, in the Simulink program we should coordinate the movements of all elements in order to achieve the motion of robot. The Simulink model of robot is shown as Fig. 4 which includes six parts, displacement input from workspace (DI), base rotation (BR), slides components movement (SC), end-effector movement (EE) and virtual reality toolbox (VR).

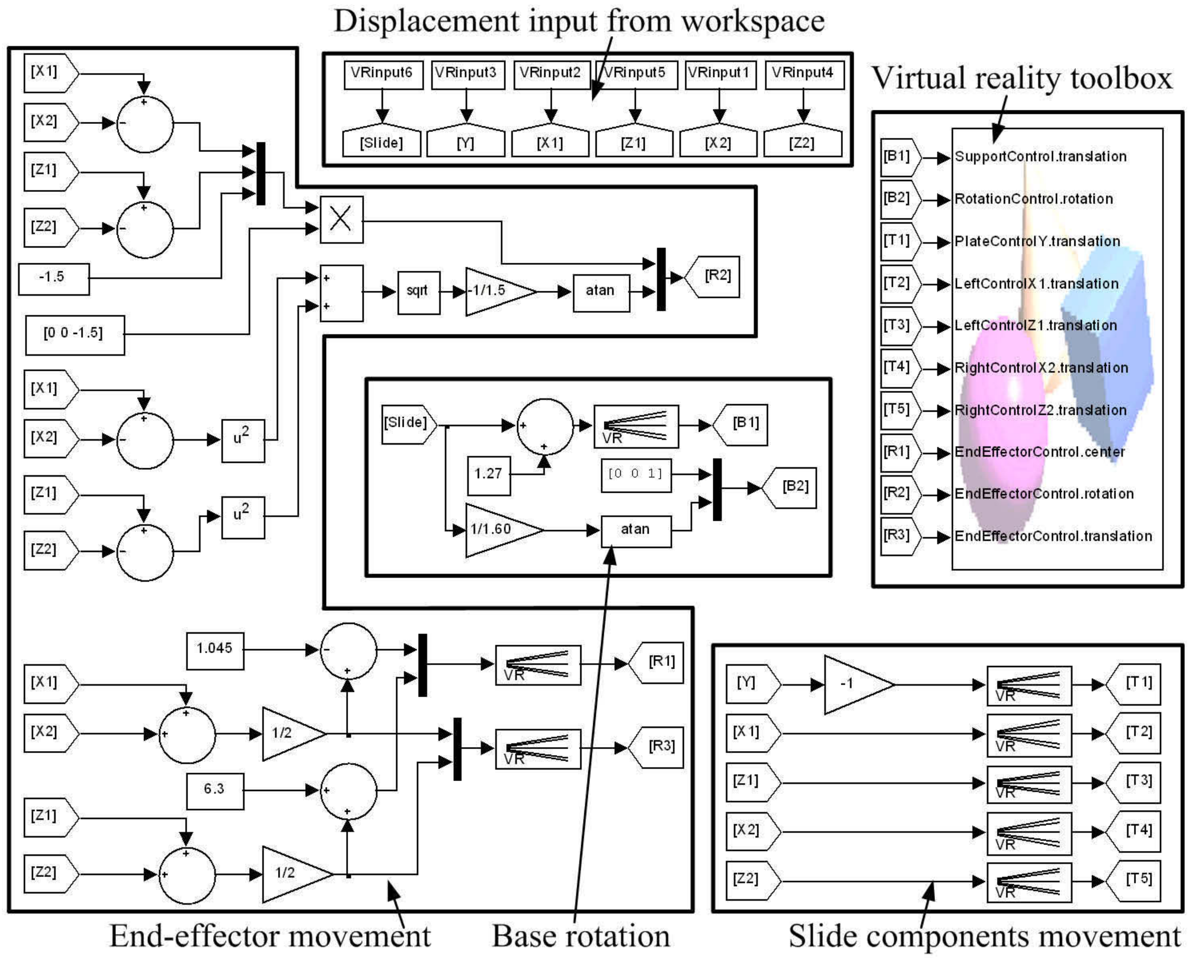

Fig. 4: Simulink model of the robot.

In the clinical application of robot assisted reduction surgery, the pre-operative or intra-operative reduction path is defined by a series of pose of the distal fragment (connected to the end-effector). Using the inverse kinematics as shown in Section 2.2, we calculate out the relative displacement of all the actuators. And by import a series of displacement data of all the actuators to the Simulink program, a 3D simulation reduction path will be shown to the surgeon for following revision or execution of the reduction path.

DI sub-model is used to import to Simulink program the data of displacement in each actuator that is computed by inverse kinematics. VRinput1-VRinput6 is relative to the displacement of actuators 1-6.

Base rotation sub-model is to coordinate the movements of lower sleeve and lower base. As the lower platform serves as the tilting joint, if the element of lower sleeve (actuator 1#) is uplifted, the element of lower base will be rotated about Y-axis correspondingly, and the pose of other related elements defined in hierarchy chain structure will be changed.

Slide components movement sub-model is used to control the movement of all slide elements (actuators 1#-5#).

End-effector movement sub-model controls the movement of the end-effector. After calculate out the displacement of all the actuators, we obtain the position and orientation of the end-effector using the inverse kinematics, and then we can control the pose of the end-effector using the end-effector movement sub–model, to change the pose of the distal fragment of femur connected to the end-effector.

The Virtual reality toolbox connects the Simulink program with virtual environment constructed by V-Realm Builder 2.0.

3 VIRTUAL TELE-OPERATION

In robot assisted femur fracture reduction surgery, the surgeon is required to plan a reduction path for the surgery. The reduction path is defined by a series of pose (position & orientation) of the femur fragments. One solution is to input values of the pose of the femur fragments through keyboards and mouse, but these values, especially the values of orientation is often obscure to the surgeon. Westphal et. Al. [5] proposed a solution to control the fragment using a 2 DOF joystick, by switching between rotational and translational manipulation mode and changing from different viewing direction, to complete 3D fracture reduction path. However, using a joystick is still inconvenient and less intuitive as frequently switch and changing of viewing direction is required. Our objective is to develop a convenient tele-operation interface system for surgeons to define a pre-operative or intra-operative path based on a 6-DOF haptic interface Phantom [24].

Fig. 5 shows the 6-DOF Phantom device and its geometric structure. User moves the HIP to change its pose. In our virtual tele-operation system, the distal fragment is connected to the end-effector of the robot model. When a user manipulates the robot model using a haptic device, the tool frame of the robot end-effector must be kept consistent with that of the haptic interface. Therefore we link the TCP of the robot model to the HIP of the phantom device, and in this mode, the TCP of a robot is manipulated by the HIP as shown in Fig. 6.

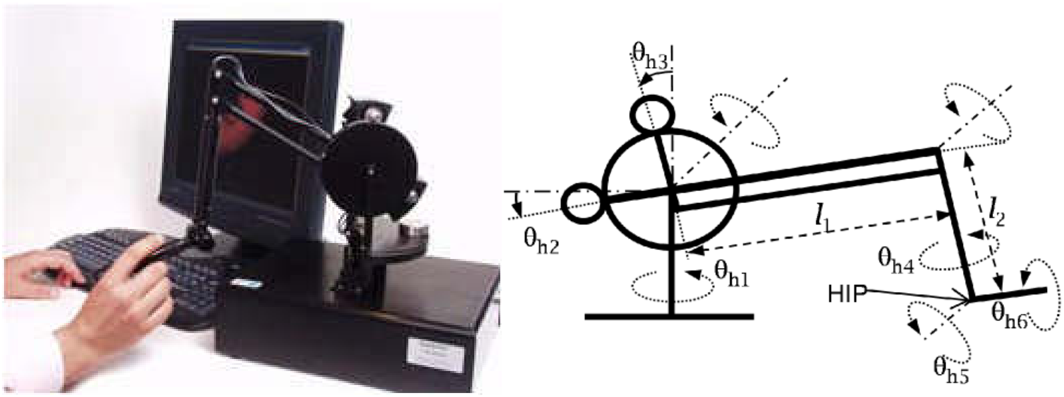

Fig. 5: Geometric structure of the haptic interface [25].

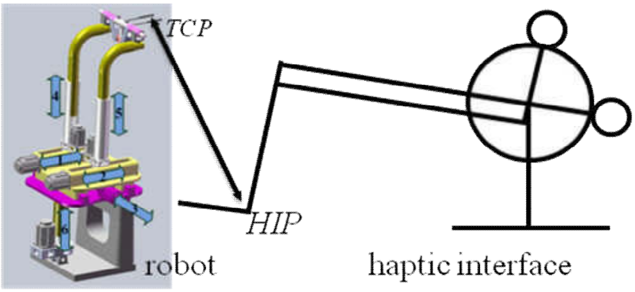

Fig. 6: Tele-operation method: link the TCP to HIP.

When the surgeon defines a pre-operative or intra-operative path using the tele-operation system, firstly, he/she moves the HIP, the system traces the transformation of the haptic interface ($\boldsymbol{X}_h$) in haptic workspace. Then, it converts the transformation to the virtual robot model ($\boldsymbol{X}_m$). With the obtained pose, $\boldsymbol{X}_m$, we can calculate the pose of the TCP of the robot model, and then using the inverse kinematics described in section 2.2, we obtain the displacements of corresponding actuators. Then the virtual robot model is updated according to the calculated displacements. When the femur fragment is moved to one desired pose, the surgeon stops moving the HIP, and presses the button on the haptic device, the system takes a record of the inter-pose. And then the surgeon continues moves the HIP to obtain another inter-pose. The surgeon iterates the process until he reaches the final pose. Fig. 7 shows the motion of the virtual robot in re-aligning a bone fragment.

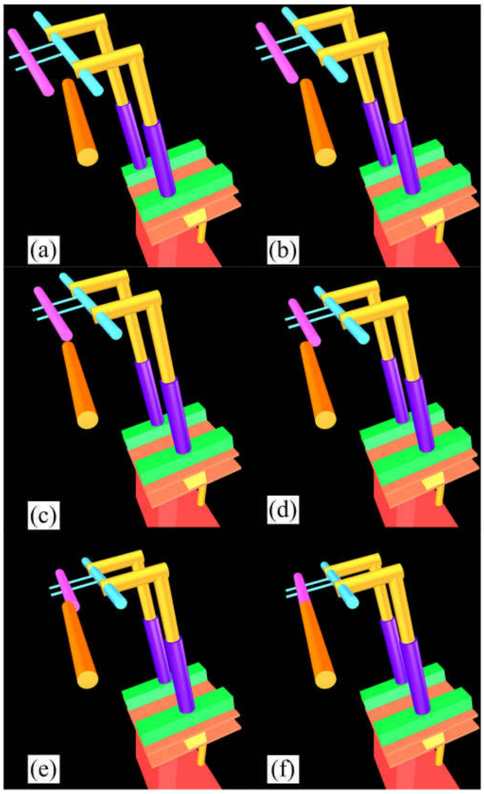

Fig. 7: Motion of the robot in virtual environment.

4 DISCUSSIONS AND CONCLUSIONS

The simulation has validated the kinematics analysis of the robot. Motion simulation of the proposed robot is accomplished under a virtual tele-operated haptic interface, MATLAB Simulink and virtual reality toolbox. Simulation result shows that the two bone fragments can be realigned correctly and motion of the robot can accurately follow the user's instructions in the virtual environment. These results demonstrate the validity of analyzed kinematics of the robot, and show that the Simulink model could correctly coordinate the virtual components and achieve planned motion of the robot.

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