Geometric and Kinematics Modeling of Tele-operated Virtual Construction Robot

Xiao Li
School of Electromechanical Engineering, Guangdong University of Technology, Guangzhou, China
Email: lixiao@gdut.edu.cn

Zhifeng Huang
Chen De Plastics Machinery Co., Ltd., China
Email: 18025957848@189.cn

Haotian Li
Department of Computer and Information Science and Engineering, University of Florida, Gainesville, USA
Email: haotianli@ufl.edu

Abstract—The tele-operated virtual construction robot is an important part of the tele-operated construction robot system based on virtual reality. To improve the realness of the virtual construction robot and reduce the difficulty of development, the hybrid modeling method of combining OpenGL function modeling with Solidworks software modeling, along with the Denavit-Hartenberg (D-H) method were investigated and applied to the geometric and kinematics modeling of the virtual construction robot. The simulation experimental results demonstrated that the motions of virtual construction robot and real construction robot are consistent, and the position and attitude of the mechanical gripper fingertips of both are the same and are consistent with the theoretical results. The modeling method is feasible and effective, which can provide some references to the construction robot modeling with similar structure.

***Index Terms*—tele-operated virtual construction robot, geometric modeling, kinematics modeling**

I. INTRODUCTION

The tele-operated construction robot system is remote operating systems that can complete complex engineering tasks under the operation of human beings. It can help human beings work in dangerous and extreme environment. However, there is a large time-delay in the signal transmission between the operator and the remote construction robot. So the stability and maneuverability of the system are greatly influenced. With the rise of virtual reality technology, virtual reality-based prediction technology has been used by many researchers [1-6]. Using virtual reality technology in the tele-operated construction robot system, the time-delay influence to the system can be effectively resolved. This method helps the operator to know the information of the work site better and improving the work efficiency of the tele-operation.

The tele-operated virtual construction robot is an important part of the tele-operated construction robot system based on virtual reality. In the theoretical conditions, as long as the virtual environment is consistent with the real environment, the state changing of virtual construction robot can be reflected in the real environment. Therefore, the modeling of the virtual construction robot is particularly important. Appropriate modeling method can meet the realistic model requirement, and can reduce modeling difficulty.

The modeling of tele-operated virtual construction robot mainly include two aspects, which are geometric modeling and kinematics modeling.

Currently, Denavit-Hartenberg (D-H) method is commonly used in the kinematics modeling of robot. This modeling method is simple and widely applied. There are two main ways in geometric modeling. One is by invoking functions of 3-D graphics library and modeling with computer programming language. This method is conducive to the motion control of close-loop linkage model, but it cannot describe complicated objects and has a difficult development and poor simulation results [7][8]. The other one is by using 3-D graphics softwares as a support. This method is easy to realize an accurate geometric modeling of complicated objects, and has good portability as well as high modeling efficiency [9][10]. Among the commonly used graphical tools, OpenGL graphics library has the traits of powerful function, high efficiency, good portability and independency within each system. So based on Visual C++ and OpenGL, the virtual construction robot is developed in this paper. Moreover, the hybrid modeling method of combining OpenGL function modeling with Solidworks software modeling along with the D-H method were investigated and applied to the geometric modeling and the kinematics modeling of the virtual construction robot. The experimental results show that the modeling method is feasible and effective. And the virtual construction robot shows good simulation results.

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II. Geometric Modeling of Virtual Construction Robot

To ensure the consistency of the robot motion locus of construction robot and virtual construction robot, both dimensional proportion of each part should be the same. Since the motion of virtual construction robot should be controlled, the construction robot can be split into several parts according to its motion and each part is modeled respectively.

The construction robot in the tele-operated construction robot system based on virtual reality in this paper is mainly composed of base, swing, boom, arm and mechanical gripper, as shown in Fig. 1. The mechanical gripper, arm, boom and swing include a number of connecting rods and servo hydraulic cylinders. The construction robot grabs objects by moving four servo hydraulic cylinders [11]. The four servo hydraulic cylinders, combined with the adjacent connecting rod respectively, form a close-loop linkage mechanism. So their structures are complex and modeling is difficult.

According to the characteristics of construction robot and each modeling method, this paper adopts the hybrid modeling method of OpenGL function modeling and Solidworks modeling to the geometric modeling of virtual construction robot. In these methods, the modeling of hydraulic cylinders use OpenGL function modeling method and use Solidworks modeling method for the rest parts. The hybrid modeling method can improve the efficiency of modeling and improve the accuracy of modeling.

Fig. 2 shows the geometric modeling processes of the virtual construction robot. And detail modeling processes are as follows:

(1) Except the hydraulic cylinders, the construction robot is drawn into nine parts by Solidworks software, i.e. base, swing, boom, arm, fixed plate, upper gripper, lower gripper, gripper rods and knighthead. And the model data source files are generated as STL format.

(2) Import the nine STL format files to 3D MAX respectively and put the joint point of the models on the zero position using the functions of move and rotate in 3D-MAX, then export them as 3ds format files. The related rendering processing of the models can be done under the 3D-MAX environment.

(3) Under VC++ environment, load the nine 3ds format files to program by invoking loading function load3djobj(char* dir,char* cn,int a) of the specialized class CLoad3DS(), and display the imported models by invoking display function show3ds(int jo,float tx,float ty,float tz,GLbyte Red,GLbyte Green,GLbyte Blue,float size).

(4) According to the coordinate values of the related joint points on the connecting rods, we use the OpenGL modeling function to model the four servo hydraulic cylinders. By using this method, the extension and contraction of the piston rod of the hydraulic cylinders can be controlled freely.

Simultaneously, use OpenGL related functions to process light, materials, textures and anti-aliasing of the virtual environment to make the model look more realistic. The completed virtual construction robot model is shown in Fig. 3.

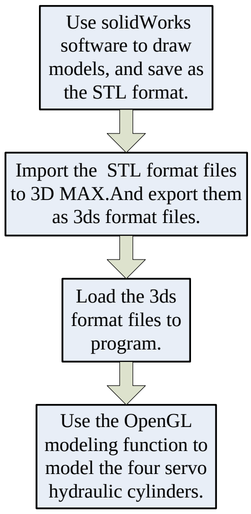

Figure 2. Flow chart of geometric modeling of virtual construction robot.

Figure 1. Construction robot in tele-operated construction robot system.

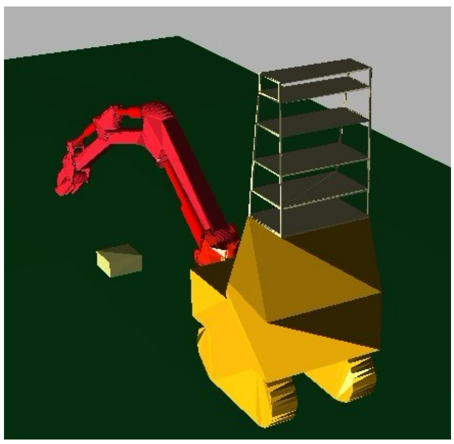

Figure 3. Geometric model of virtual construction robot.

III. KINEMATICS MODELING OF VIRTUAL CONSTRUCTION ROBOT

The kinematics modeling of the robot is to confirm the position and attitude relation between the articulated rods according to the length and rotation angle of the robot's articulated rods. It is the base of the robot motion control. The D-H method is the most commonly used one in robot kinematics analysis. In this paper, the D-H method is adopted for the kinematics analysis of the virtual construction robot

A. Establishment of Virtual Construction Robot Coordinate System

It is the premise of the kinematics analysis to establish the coordinate system of each linkage mechanism. In order to make the virtual construction robot's movement be consistent with that of the real construction robot, all of the coordinate systems are set in the joint point of each rod piece.

The calibration of the coordinate system for each of the member bar of the virtual construction robot in this paper is shown in Fig. 4. Set the coordinate system of the base, which is consistent with the OpenGL screen coordinate system, as the base coordinate system, namely $X_0Y_0Z_0$. The coordinate system of the swing connected with the base is set to be $X_1Y_1Z_1$. The coordinate system of the boom hinged with the swing is set to be $X_2Y_2Z_2$. The coordinate system of the arm linked with boom is set to be $X_3Y_3Z_3$. The coordinate system of the upper gripper jointed with arm is set to be $X_4Y_4Z_4$ and the coordinate system of the upper gripper end is set to be $X_5Y_5Z_5$.

B. Kinematics Equations of Virtual Construction Robot

According to the coordinate systems established above, the position and attitude of one local coordinate system relative to the previous one is described by Homogeneous transformation matrix Ai. Namely, $A1$ describes the position and attitude of coordinate system $X_1Y_1Z_1$ relative to the one of $X_0Y_0Z_0$, $A2$ describes the position and attitude of coordinate system $X_2Y_2Z_2$ relative to the one of $X_1Y_1Z_1$ and so, $A5$ describes the position and attitude of coordinate system $X_5Y_5Z_5$ relative to the one of $X_4Y_4Z_4$.

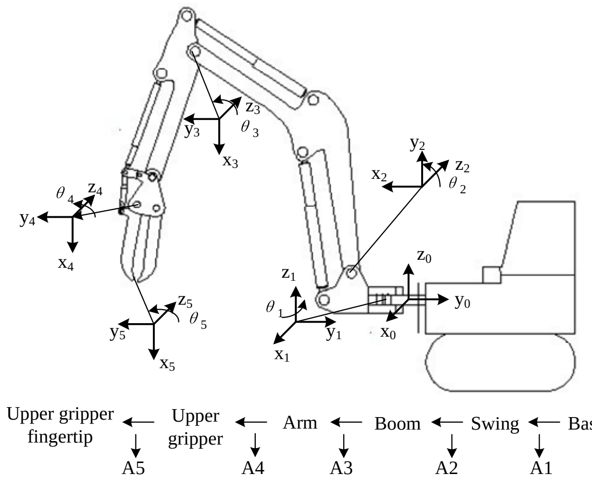

Figure 4. Calibration of virtual construction robot's coordinate system.

In accordance with the structure of the virtual construction robot, the motion of each connecting rod and the coordinate value of each joint point relative to previous coordinate system, each position and attitude transformation matrix can be calculated as follows:

$$A1 = \begin{bmatrix} C_1 & 0 & S_1 & X_1 \\ 0 & 1 & 0 & Y_1 \\ -S_1 & 0 & C_1 & Z_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (1)$$

$$A2 = \begin{bmatrix} -C_2 & -S_2 & 0 & X_2 \\ -S_2 & C_2 & 0 & Y_2 \\ 0 & 0 & -1 & Z_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (2)$$

$$A3 = \begin{bmatrix} -S_3 & C_3 & 0 & X_3 \\ -C_3 & -S_3 & 0 & Y_3 \\ 0 & 0 & 1 & Z_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (3)$$

$$A4 = \begin{bmatrix} C_4 & S_4 & 0 & X_4 \\ -S_4 & C_4 & 0 & Y_4 \\ 0 & 0 & 1 & Z_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (4)$$

$$A5 = \begin{bmatrix} C_5 & S_5 & 0 & X_5 \\ -S_5 & C_5 & 0 & Y_5 \\ 0 & 0 & 1 & Z_5 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (5)$$

The coordinate system $X_0Y_0Z_0$ is served as reference coordinate system. The position and attitude transformation matrixes of the coordinate system $X_1Y_1Z_1$, $X_2Y_2Z_2$, $X_3Y_3Z_3$ and $X_4Y_4Z_4$ are ${}^0T_1$, ${}^0T_2$, ${}^0T_3$ and ${}^0T_4$ respectively.

The position and attitude transformation matrix of the upper gripper end's coordinate system relative to the base's coordinate system is ${}^0T_5$. Multiplied by each transformation matrix Ai, the position and attitude matrix of the upper gripper fingertip can be obtained:

$${}^0T_5 = A1A2A3A4A5 = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (6)$$

And the position equations of the upper gripper fingertip are:

$$\begin{aligned} p_x = {} & X_5\left[C_1C_2(S_3C_4+C_3S_4)+C_1S_2(C_3C_4-S_3S_4)\right] \\ & +Y_5\left[C_1C_2(S_3S_4-C_3C_4)+C_1S_2(C_3S_4+S_3C_4)\right]-S_1Z_5 \\ & +C_1C_2(S_3X_4-C_3Y_4-X_3)+C_1S_2(C_3X_4+S_3Y_4-Y_3) \\ & -S_1(Z_3+Z_4)+C_1X_2+S_1Z_2+X_1 \end{aligned}. \quad (7)$$

$$\begin{aligned} p_y = {} & X_5[S_2(S_3C_4 + C_3S_4) - C_2(C_3C_4 - S_3S_4)] \\ & + Y_5[S_2(S_3S_4 - C_3C_4) - C_2(C_3S_4 + S_3C_4)] \\ & + S_2(S_3X_4 - C_3Y_4 - X_3) - C_2(C_3X_4 + S_3Y_4 - Y_3) \\ & + Y_1 + Y_2 \end{aligned} \quad (8)$$

$$\begin{aligned} p_z = {} & -X_5[S_1C_2(S_3C_4 + C_3S_4) + S_1S_2(C_3C_4 - S_3S_4)] \\ & - Y_5[S_1C_2(S_3S_4 - C_3C_4) - S_1S_2(C_3S_4 + S_3C_4)] \\ & - C_1Z_5 - S_1C_2(S_3X_4 - C_3Y_4 - X_3) \\ & - S_1S_2(C_3X_4 + S_3Y_4 - Y_3) - C_1(Z_3 + Z_4) \\ & + C_1Z_2 - S_1X_2 + Z_1 \end{aligned} \quad (9)$$

The attitude equations of the upper gripper fingertip are:

$$\begin{aligned} n_x = {} & C_5[C_1C_2(S_3C_4 + C_3S_4) + C_1S_2(C_3C_4 - S_3S_4)] \\ & - S_5[C_1C_2(S_3S_4 - C_3C_4) + C_1S_2(C_3S_4 + S_3C_4)] \end{aligned} \quad (10)$$

$$\begin{aligned} n_y = {} & C_5[S_2(S_3C_4 + C_3S_4) - C_2(C_3C_4 - S_3S_4)] \\ & - S_5[S_2(S_3S_4 - C_3C_4) - C_2(C_3S_4 + S_3C_4)] \end{aligned} \quad (11)$$

$$\begin{aligned} n_z = {} & C_5[-S_1C_2(S_3C_4 + C_3S_4) - S_1S_2(C_3C_4 - S_3S_4)] \\ & + S_5[S_1C_2(S_3S_4 - C_3C_4) + S_1S_2(C_3S_4 + S_3C_4)] \end{aligned} \quad (12)$$

$$\begin{aligned} o_x = {} & S_5[C_1C_2(S_3C_4 + C_3S_4) + C_1S_2(C_3C_4 - S_3S_4)] \\ & + C_5[C_1C_2(S_3S_4 - C_3C_4) + C_1S_2(C_3S_4 + S_3C_4)] \end{aligned} \quad (13)$$

$$\begin{aligned} o_y = {} & S_5[S_2(S_3C_4 + C_3S_4) - C_2(C_3C_4 - S_3S_4)] \\ & + C_5[S_2(S_3S_4 - C_3C_4) - C_2(C_3S_4 + S_3C_4)] \end{aligned} \quad (14)$$

$$\begin{aligned} o_z = {} & -S_5[S_1C_2(S_3C_4 + C_3S_4) + S_1S_2(C_3C_4 - S_3S_4)] \\ & - C_5[S_1C_2(S_3S_4 - C_3C_4) + S_1S_2(C_3S_4 + S_3C_4)] \end{aligned} \quad (15)$$

$$a_x = S_1. \quad (16)$$

$$a_y = 0. \quad (17)$$

$$a_z = -C_1. \quad (18)$$

where, S_i denotes $\sin(\theta_i)$, i=1,2,..,5; C_i denotes $\cos(\theta_i)$, i=1,2,..,5; θ_i denotes the angle variables of rotating joints, i=1,2,..,5; (X_i, Y_i, Z_i) denotes the coordinate values of the i-th joint point in the coordinate system $X_{i-1}Y_{i-1}Z_{i-1}$; a_x, a_y, a_z denote the approaching vector coordinate of the upper gripper fingertip; o_x, o_y, o_z denote the direction vector coordinate of the upper gripper fingertip; n_x, n_y, n_z denote the normal vector coordinate of the upper gripper fingertip; p_x, p_y, p_z denote the position coordinate of the upper gripper fingertip in base's coordinate system.

The mechanical gripper mechanism is composed of upper gripper, lower gripper, gripper rods and a pair of meshing gears and so on. The upper and lower grippers are engaged through the gears. The position and attitude of the lower gripper can be determined by those of upper gripper. Therefore, the position and attitude transformation matrix of the lower gripper end's coordinate system relative to the base's coordinate system can be obtained. The position and attitude transformation matrixes of the upper and lower grippers are the base of the kinematics analysis and collision detection of the tele-operated virtual construction robot.

C. Kinematics Realization of Virtual Construction Robot

By using the translation function glTranslatef(), rotation function glRotatef() and the matrix stack function glPopMatrix() and glPushMatrix() in OpenGL, translate the models imported in the virtual environment to a specific position, and control them rotating around the respective joint coordinate system. Thus, the inheritance relationship of each rod piece can be established, and make the virtual construction robot move smoother by using the OpenGL double buffering technique.

IV. Simulation Experiment of Virtual Construction Robot

To prove the validity of the adopted modeling method, a tele-operated construction robot system based on virtual reality, which is mainly composed of a virtual construction robot, two Saitek force feedback joysticks and a construction robot, was established and a large number of simulation experimental studies in virtual construction robot grasping objects were conducted.

In the simulation experiment, the operator uses the force feedback joysticks to control the rotation angle of each joint on the virtual construction robot to obtain the best position and attitude of the mechanical gripper in grasping brick. The grasping operation process are as follows, first pick up the brick, then rotate the virtual construction robot to the scheduled location, and then loosen the mechanical gripper and put down the brick.

As shown in Fig. 5, three momentary pictures are captured from the simulation experimental processes. The simulation experimental results demonstrated that each connecting rod's motions of virtual construction robot are consistent with that of the real construction robot. Moreover, the position and attitude of the mechanical gripper fingertips of both are the same and are consistent with the theoretical results.

V. Conclusions

According to the structural and kinematic characteristics of construction robot, this paper adopts the hybrid modeling method of OpenGL function modeling and Solidworks modeling for virtual construction robot's geometric modeling, and employs the D-H method for virtual construction robot's kinematics modeling. The simulation experimental results show that the modeling method is feasible and effective. The 3D modeling and motion control of the virtual construction robot are realized perfectly and also has some references to the construction robot modeling with similar structure.

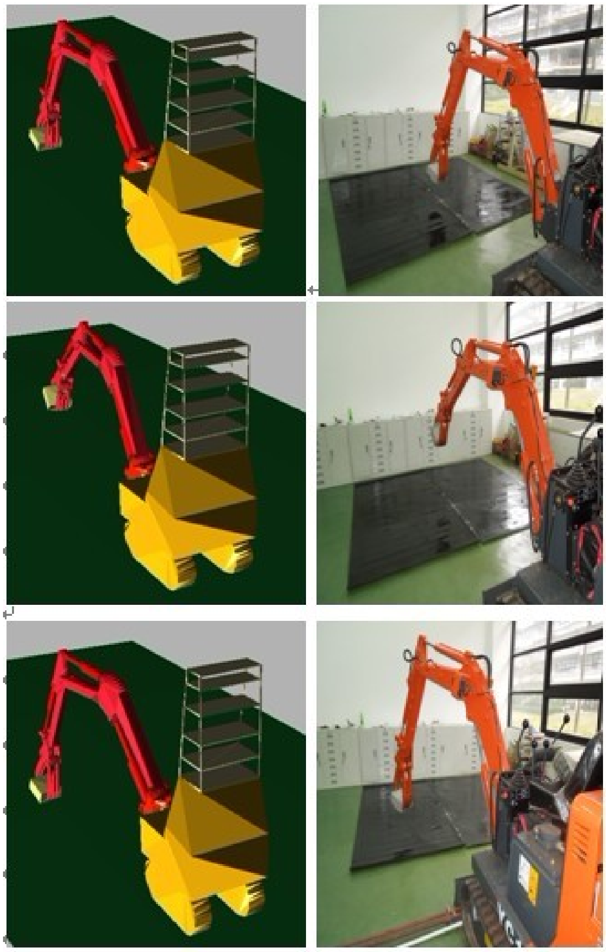

Figure 5. Movement instant attitudes of both virtual construction robot and real construction robot.

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Xiao Li was born in Liaoning, China, in 1962. He received the Ph.D. degree in mechanical manufacturing and automation from Northeastern University, Shenyang, China, in 1999.
He is currently a Professor at the School of Electromechanical Engineering, Guangdong University of Technology, Guangzhou, China. His research interests are in the areas of automation and robotics, simulation and control of electrohydraulic system, biomedical equipment. His published works appear in several refereed journals, including *Journal of Mechanics*, *Journal of Convergence Information Technology* and *Journal of System Simulation*.
Dr. Li is a Fellow of the Chinese Mechanical Engineering Society.

Zhifeng Huang was born in Jiangxi, China, in 1984. He received the M.S. degree in Electromechanical Engineering from Guangdong University of Technology, Guangzhou, China, in 2012.
He is currently working at Chen De Plastics Machinery Co., Ltd., China.

Haotian Li was born in Liaoning, China, in 1989. He received the B.S. degree in Computer Science and technology from South China University of Technology, Guangzhou, China, in 2012.
He is currently working toward the M.S. degree at Department of Computer and Information Science and Engineering, University of Florida, Gainesville, USA.