A Collision Detection Approach in Virtual Environment of Micromanipulation Robot

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Abstract

Operators suffer much difficulty in manipulating micro-size objects without the assistance of friendly interfaces due to the scaling effects in micro world. The paper presents a general framework for micromanipulation robot based on virtual reality technology. Based on this, we bring forward a FDH (Fixed Direction Hulls) based bounding box method to handle the collision detection of the peg-in-hole microassembly successfully. The collision response model for the collision between micro needle and hole is presented. The virtual force and corresponding displacement can be calculated with the model of bending deformation and pressing deformation. Experiments verify the validity of collision response model.

Key words: micromanipulation, virtual reality, microassembly, collision detection, collision response

0. Introduction

A micromanipulation robot is widely used to operate genes and inspect integration circuits by using a stereoscopic microscopic. Micromanipulation systems with high precision and high intelligence to fulfill tasks are urgently demanded [1]. Micromanipulation refers to manipulation with the micro objects in the magnitude of micrometer [2][3]. Such precise work brings heavy burdens as follows: firstly, the vision information provided by the microscope and the CCD camera is two dimensional, unclear and limited, which cannot be observed from the other angle or viewpoint, so the operator is easy to get visual fatigue; secondly, since the characteristic of micromanipulation is high precision and small working place, any operating error can lead to the failure of the entire manipulation process. It is necessary to perform the micromanipulation with the aid of visual, tactile and force feedback by introducing virtual reality technology. The projects in this field were focused in Japan [4] [5], Europe [6][7] and America [8].

The framework of the micromanipulation virtual reality system we proposed is described in figure 1. The micromanipulation robot in this system is a 6 DoF robot. It is made up of macro motion parts and micro motion parts. Since the manipulator has 3 DoF, the master hand applied in the system at least has 3 DoF. Here we applied decoupling pantograph structure to design the master hand. With the master hand, force feedback can be achieved when the peg-in-hole microassembly task is taken either in virtual environment or in really micromanipulation. Megellan Spacemouse can provide 6DoF (3 translate and 3 rotate) to the operator.

The virtual environment for micromanipulation robot is carried out using the OpenGL graphics library and Visual C++. Figure 2 and figure 3 show the macro model and the micro model.

Geometry modeling is the foundation of virtual environment of micromanipulation robot. Physical modeling adds physical property to geometry model, and makes the model behave more like that of the real micromanipulation robot. Combining the geometry and physical modeling provides the method of deformation computation. In addition, according to the common sense of virtual reality, the virtual world should realistically reproduce the real world. During the peg-in-hole microassembly task, micromanipulation hand will collide with micro hole. As a result the virtual environment should have a collision handling mechanism.

The remainder of this paper is organized as follows: The discussion of collision detection will be presented in Section 2. Section 3 discusses collision response and we conclude this paper in section 4.

1. Collision detection

Collision detection (CD) has become an important research topic [9] in virtual reality research. In robot simulation field, efficient algorithms are needed to avoid the CD problem from becoming a major bottleneck of the application developed. In order to prevent objects from interpenetrating each other, collision detection is needed and give them a physically correct behavior. In the virtual environment,
Collision detection in its simplest form provides a binary answer: there is collision or there is no collision. If
there is collision, an action has to be taken to alter the trajectories of the colliding objects. This action is called collision response.

A class of collision detection methods use spatial decomposition to reduce the number of pairwise collision checks. These are algorithms using octrees, binary space partitioning trees (BSP), sphere hierarchies, oriented bounding boxes (OBB) [10]. RAPID is a publicly available collision detection library that uses OBB trees. Another method, axis aligned bounding boxes (AABB) [11], can be quickly updated and is thus usable for deformable objects. Among these methods, AABB is the quickest one but with a low precision; Sphere is only proper for objects frequently rotating; OBB is the tightest and most precisely one needing huge computation with a low speed. According to the feature of micromanipulation robot (high precision and micro deformation), here we bring forward FDH based bounding box algorithm with a proper precision and a proper speed.

Bounding volume hierarchy is an effective method to resolve the intrinsic time complexity in collision detection[12]. FDH is a special convex hull, whose outward normal of facets comes from a fixed direction set. It overcomes limitation of other bounding volumes and promises to give a better tightness and simplicity.

1.1 Construction of the FDH tree and sequence of collision detection

It is convenient to construct FDH tree for the geometry modeling using tree-node. At first we add a bounding box node to the leaf node which needing collision detection using the function CxAddNode. Then we use CxSetRefPose function to adjust the position and orientation between the bounding box node and its parent node. Next we construct a FDH bounding box using CxMakeBox function and setup the attribute of the node of bounding volumes box as needing testing node. With the consideration of computation time and real-time needing, we only focus on the intersection between the end of micromanipulation tools and operated objects. So we only construct the end of left hand and right hand of micromanipulation robot in the virtual environment. After the completion of the FDH bounding volumes box, we can test the collision detection. In figure 4, the model of Needle-Hole and its bounding box is presented. Here, we must presume that the checked object is static. Firstly we should check whether the micromanipulation robot transfers. If it transfers but not touches each other, the position and orientation between operating tool and operated objects change while the geometry attribute and topology structure not change. As a result, it is not used to reconstruct the FDH tree. Next it use CxCheckIntx function to check whether FDH bounding box of left hand collide with FDH bounding box of right hand. If it does, it outputs the mark to the bounding box and continues to wait for the next movement of the robot.

1.2 Construction of the FDH bounding box of micro needle and micro hole

The reconstruction of FDH bounding box needs much time and a great deal computing time, as a result it influences the performance of real-time. For the model of
micro needle, we introduce the Finite Element Method (FEM) to divide the peg in segment. Only several segments of the end is constructed with FDH bounding box to reduce the computing time. The FEM dividing is presented as figure 5.

FDH only provides intersection between convex. For the model of micro hole it is concave polyhedron so it needs convex decomposition as figure 6.

1.3 Peg-in-hole collision detection testing

After the bounding box of the end of micro needle and micro hole is constructed, we test the intersection checking between micro needle and micro hole solid, between micro needle and micro holewall, between micro needle and micro hole base respectively. T means they collide with each other, otherwise F. After the analysis of collision detection in detail, we get 4 items as figure 7.

In D mode it only detects the collision between peg and hole and not means that peg-in-hole task fails. The analysis of previous state before collision can help to analyze the micro forces. If it is the mode A between peg and hole, the peg is influenced by tangent stress from the holewall. If it is the mode B before collision, the peg fails to insert into the hole. The peg is influenced by longitudinal compressive stress.

2. Collision response

Collision response in micromanipulation virtual environment involves response to collision when the collision is being checked. In other words, virtual environment computes the virtual forces real-time and gives force feedback to the operator via the master hand; on the other hand, virtual environment should forecast the deformation of micro objects under the virtual forces and update FDH collision detection tree to provide instruction information to future collision detection. The stiffness of micro hole base is much larger than the micro needle, so the deformation focus on the micro needle.

In order to discuss virtual force and deformation of micro needle, two hypotheses are proposed here: (1) When peg collides with hole, the base of micro hole is rigid and has no deformation and only the micro needle has deformation. (2) The material of the micro needle is even and continuous. (3) The deformation of the micro needle is elastic. (As the force on peg is off, the micro needle resumes to its initial state.)

There are two kind of deformation of micro needle: (1) When peg has been in the hole, micromanipulation right hand movement will make micro needle bending deformation by tangent stress. (2) When the peg is still not in the hole, micromanipulation left hand movement will make micro needle collide with the brim of the hole and the force on the peg is longitudinal compressive stress. The analysis of two kind of force is presented as follows.
2.1 Bending deformation

In figure 8, the force P on micro needle is at a tangent of Y. The planar curve \( v = f(x) \) at XOY coordinate system is the bending curve. The curvature of curve expresses as follows:

\[
\frac{1}{\rho(x)} = \frac{\frac{d^2v}{dx^2}}{\left[1 + \left(\frac{dv}{dx}\right)^2\right]^{\frac{3}{2}}}
\]

(1)

According the rule of material bending, that is,

\[
\frac{1}{\rho} = \frac{M}{EI_z}
\]

(2)

where \( M \) is torque, \( E \) is elastic modulus value, \( I_z \) is rotation inertia. By simplify Equations (1) and (2), we have,

\[
\pm \frac{\frac{d^2v}{dx^2}}{\left[1 + \left(\frac{dv}{dx}\right)^2\right]^{\frac{3}{2}}} = \frac{M(x)}{EI_z}
\]

(3)

In micromanipulation system, the deformation of micro needle is generally little, so \( \theta = dv/dx \) is no

\[
M(x) = -P(l - x) = P(x - l)
\]

(5)

With the Equation (4) and (5) above and initial condition, the angel and curve express as follows,

\[
\theta = \frac{P}{EI_z} \left(\frac{x^2}{2} - lx\right)
\]

(6)

\[
v = \frac{P}{EI_z} \left(\frac{x^3}{6} - \frac{lx^2}{2}\right)
\]

(7)

Let \( x = l \), the max value is,
\[ \theta_{\text{max}} = \theta_{x=x_l} = -\frac{P l^2}{2EI_z} \]  
(8)

\[ v_{\text{max}} = v_{x=x_l} = -\frac{P l^3}{3EI_z} \]  
(9)

During the collision between micro needle and hole, the depth of intersection can be computed by the DC program. Since object can’t traverse each other, the depth is \( v_{\text{max}} \). So the virtual force on micro needle when the needle touches the micro hole is,

\[ P = -\frac{3v_{\text{max}}EI_z}{l^3} \]  
(10)

After virtual force \( P \) is figured out, the deformation of the micro needle can be computed by Equation (8) and (9). For we divide the micro needle into parts, so each part deformation can be figured out.

![Force curve of bend deformation](image1)

**Fig. 10 Force curve of bend deformation**

![Force curve of press deformation](image2)

**Fig. 11 Force curve of press deformation**

There is collision between peg and hole wall before micro needle inserts into the hole for the position and orientation error. The force on the needle is axial compressive stress and stay as beeline equilibrium state. Figure 9 presents the deformation under a given force. In this figure, we amplify the deformation. The function relation
among the deformation $X_0$, $Y_0$ and compressive force $P$ is presented as follows.

According to Equation (3), we have,

$$\frac{d^2v}{dx^2} = \frac{M(x)}{EI_z} = -\frac{Pv}{EI_z} \tag{1}$$

Let $K^2 = \frac{P}{EI_z}$, Equation (1) simplified as,

$$\frac{d^2v}{dx^2} + K^2 v = 0 \tag{2}$$

To solve the equation above we get,

$$v = \delta (1 - \cos \frac{\pi x}{2l}) \tag{3}$$

The deformation of micro needle is the max value $\delta$ at the end $x = l$. But $\delta$ is not a certain value.

Using complete elliptic integral, what we get is,

$$X_0 = \frac{2E_{\theta_0/2}l - K_{\theta_0/2}l}{K_{\theta_0/2}} \tag{4}$$

$$Y_0 = \left( \frac{2l}{K_{\theta_0/2}} - l \frac{E_{\theta_0/2}}{E_{\theta_0/2}^2} \right) \sin \frac{\theta_0}{2} \tag{5}$$

$$P = \frac{EI_z}{l^2} \left( K_{\theta_0/2} \right)^2 \tag{6}$$

where

$$K_{\theta_0/2} = \int_0^{\pi/2} \frac{1}{\sqrt{1 - a^2 \sin^2 \phi}} d\phi$$

$$E_{\theta_0/2} = \int_0^{\pi/2} \sqrt{1 - a^2 \sin^2 \phi} d\phi$$

$a = \sin \frac{\theta_0}{2}$, $\theta_0$ is the angel of deformation of the free part.

So we get that $X_0$, $Y_0$ and $P$ all is the function of $\theta_0$. From exploring the table of complete elliptic integral, we can get the value of $X_0$, $Y_0$ and $P$. Together with (3), every relative displacement of small dividing part can be figured out.

3 Experiment

To verify to validate of model of virtual force, experiment of bending deformation and pressure deformation is carried out in our research.

In the bending deformation experiment, we get force sensor data setup under micro hole. Using min double multiplying, we get the value of $EI_z$, therefore we get the value of virtual force. The contrast between virtual force and real force is presented in figure 10.

In figure 11, it presents the axial deformation, tangent deformation and virtual force with the axial compressive force.

4 Conclusion

In our research, we set up a virtual manipulation platform for the micro world to supervise the manipulation process and virtual environment corresponding to the actual micromanipulation system to preview or simulate motion plan before the actual manipulation. The operator can monitor the microassembly through the master hand with force feedback together with vision feedback.

In virtual environment, the virtual objects should not only reflect the shape characters of the actual objects, but also reflect the physical characters of the actual world. To avoid the collision between virtual objects, we analyze the collision check mathematic models, and set up a collision check model based on FDH bounding box method. The deformation of micro objects under micro force is studied. After analyzing the states of the micro needle during the peg-in-hole process, the differential equation of micro needle’s deformation is given. The deformation and virtual force are fed back to the operator. Experiment show that the model is valid and efficient for collision detection of micromanipulation robots.

References

