# STUDY ON VIRTUAL MANIPULATION TECHNOLOGY IN VIRTUAL REALITY SYSTEMS

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Abstract: In this paper, virtual manipulation technology is investigated for a class of virtual cockpit system. Firstly, a prototype is constructed for the virtual manipulation process. Then some of the key techniques involved in the virtual manipulation prototype are discussed respectively. These techniques include the tracking and modelling of hand, modelling of virtual objects, modelling of virtual force, motion analysis of virtual object and stable grasp condition, etc. It should be noted that, though the virtual manipulation prototype is developed for virtual cockpit system in this paper, it can also be implemented in other virtual reality systems, in which, hand's interaction with the virtual world is essential and necessary.

Keywords: Virtual Reality, Virtual Manipulation, Cyberglove.

## 1. INTRODUCTION

One of the important characteristics of a Virtual Reality (VR) systems is that it can make users feel to be immersed in the real world, though they are still in a virtual world. Currently, this kind of immersion greatly depends on vision feedback, which is easy to be realized in practical experiment. Due to the rapid development in computer graphics, the images generated by computers are more and more realistic, which is capable to provide vivid vision information for the users of VR systems. However, for the other senses of human beings, such as taste, smell, haptic, etc, relative little works have been done. Probably due to the technical difficulties in the research and development of sensors, force feedback devices and corresponding algorithms, etc. Being an essential interaction method between the users and the virtual space, data glove plays an important role in the study of VR. By using data glove as the inter medium, users of VR system can capture, grasp, manipulate Virtual Objects (VO) in the virtual world. In the process of the Virtual Manipulation (VM), the haptic immersion of VR systems can be obtained to some extent, though the haptic feedback provided by data glove is far from satisfactory currently.

In the past decades, researches on data glove and corresponding VM algorithms have attracted more and more interests (Tzafestas, Jan, 2003; Tarchanidis and Lygouras, 2003; Su *et al.*, 2003; Chou *et al.*, 2003; Weissmann and Salomon, 1999). In (Tzafestas, Jan, 2003), the authors investigated the problems related to the haptic interaction between the human operator and a virtual environment. The schemes proposed in that paper mainly focuses on the whole-hand kinesthetic for

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VM. Little discussions can be found for the modelling of the VM process, such as the modelling of Virtual Forces (VF) etc. In (Su *et al.*, 2003), three-dimensional electromagnetic sensors have been integrated into a data-glove to accurately model and capture the motion of the human hand. The technique described is successfully implemented in the analysis of clinic conditions, such as Parkinson's disease. The same as in (Tzafestas, Jan, 2003), the modelling of the VM process wasn't fully discussed.

Noting the need of effective algorithms and modelling analysis in VM process, in this paper, a new kind of prototype for VM is proposed, and the prototype with corresponding algorithms are applied to a virtual cockpit system (as shown in Figure 1). The main contributions of this paper are as follows: (1) a new prototype for virtual manipulation in VR systems is proposed; (2) modelling methods are discussed for hand, VO and VF respectively; and (3) a stable grasp condition in VM is proposed, which improves the VM convergence speed and at the same time reduce penetrations among VO and virtual hand.

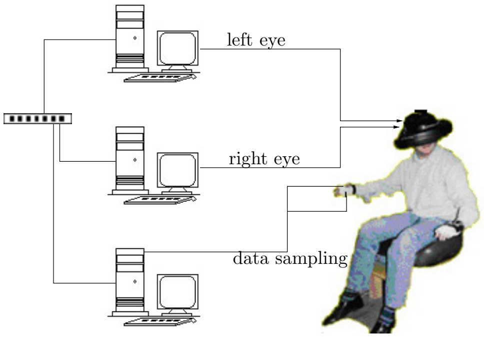

Fig. 1. Virtual Cockpit System

This paper is organized as follows. In Section 2, the prototype for the VM process is proposed, a detailed flowchart is used to illustrate the VM prototype. Tracking and modelling of hand, as well as joint coordinate transformation are discussed in Section 3. In Section 4, several specific problems in VM are discussed, including modelling of VF, modelling of dynamic virtual objects (DVO), stable grasp condition, etc. Finally, conclusions are made in Section 5.

## 2. PROTOTYPE OF THE VIRTUAL MANIPULATION

The main focus in VM study is how to render the physical interaction between users and the VO. The fundamental behaviors in a VM system consist of the following aspects: (1) moving of the hand in the virtual world; (2) the gesture adjustment when the virtual hand approaches the VO; (3) grasp and release of VO; and (4) the relocation of the VO.

In this paper, based on theoretical study, a VM prototype is constructed to describe the physical interaction procedure between users and the VO. The virtual hand, static virtual object (SVO) and DVO are considered in the VM prototype. For the SVO (such as wall and ground), They remain static in the whole VM process. Therefore, except collision detection analysis, there is no need to consider the dynamic behavior of SVO. For DVO, their states are determined by external forces. Thus, their dynamic models and behaviors should be involved in the VM prototype analysis.

In the virtual cockpit system we developed, the VM procedure can be summarized as follows:

- By data glove measurement, the virtual hand position data is sent to the central processing computer.
- The virtual hand, SVO and DVO models are generated in the central computer.
- Collision detection and VM algorithms are applied to the three kinds of virtual entities, (virtual hand, SVO and DVO).
- The states information of the VO are sent to the image generation computer, stereo images of the virtual world is displayed in the Head Mounted Display (HMD).
- Finally, based on the vision feedback, users can adjust the virtual hand position to manipulate the VO.

The flowchart of the VM prototype is shown in Figure 2. Considering the VM procedure described in Figure 2, the following problems should be considered in order to make the VM process successful:

- Tracking of the hand motion and modelling of the virtual hand: by using data glove and 6-degree sensors to measure the movement of the hand, geometric and kinetics models of virtual hand should be constructed.
- Modelling of VO: all the VO in the virtual world should have physical properties, such as mess, friction coefficient, etc, in order to make the virtual world more trueness.
- Collision detection: for the DVO, the SVO and the virtual hand, collision detection should be carried out.
- Modelling of VF: for DVO, their VF model should be constructed by considering physical parameters.
- VM algorithm: use the VF model of VO, and kinetics analysis combined with gesture analysis method, to compute the state parameters of VO.

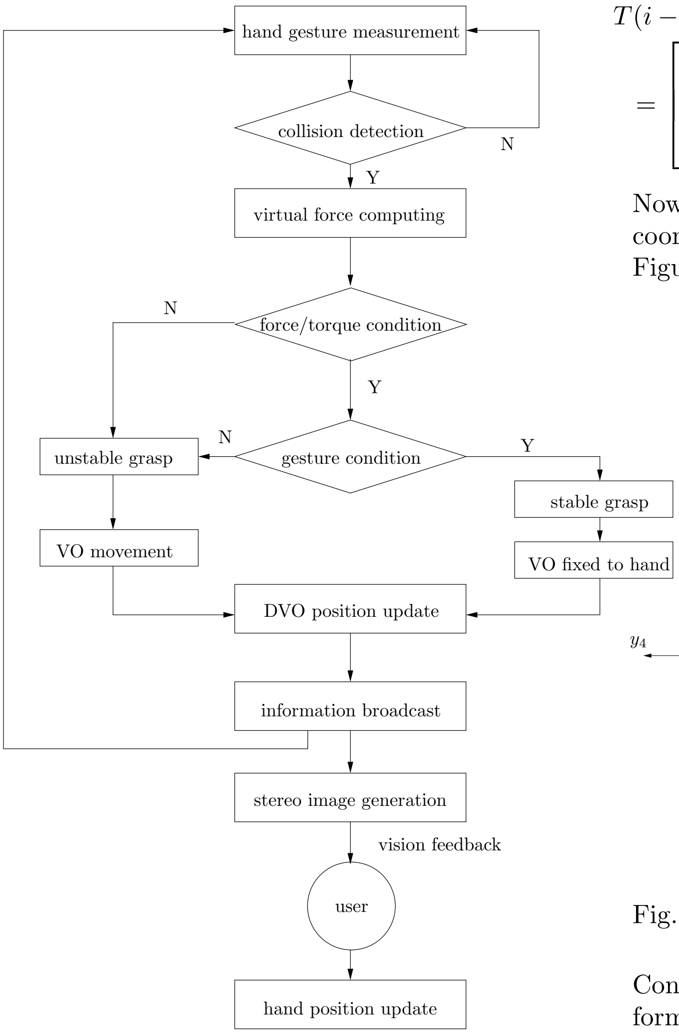

Fig. 2. Flowchart of the Virtual Manipulation

## 3. TRACKING AND MODELLING OF HAND

Modelling of the real hand is originated from the forward kinematics, (Bediz, 1997; Skopowski, n.d.). Considering the following kinesthetic coordinate and corresponding parameters as shown in Figure 3:

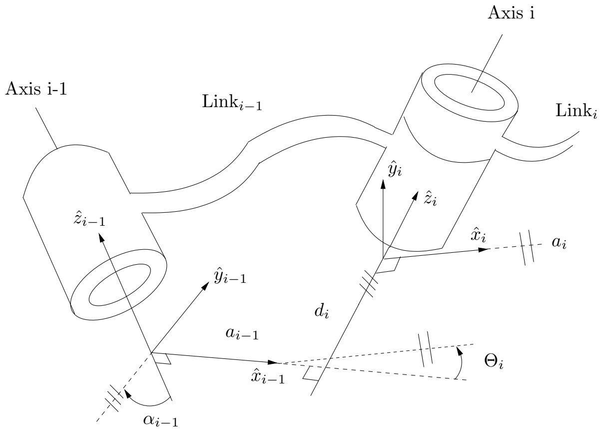

Fig. 3. kinesthetic coordinate definition

The coordinate transformation matrix from coordinate $i-1$ to $i$ can be defined as follows:

$$T(i-1,i) = \begin{bmatrix} \cos\theta_i & \sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & a_i\cos\theta_i \\ -\sin\theta_i & \cos\theta_i\cos\alpha_i & \cos\theta_i\sin\alpha_i & a_i\sin\theta_i \\ 0 & -\sin\alpha_i & \cos\alpha_i & -d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

Now, take the little finger as an example, the joint coordinate and parameter definitions are shown in Figure 4.

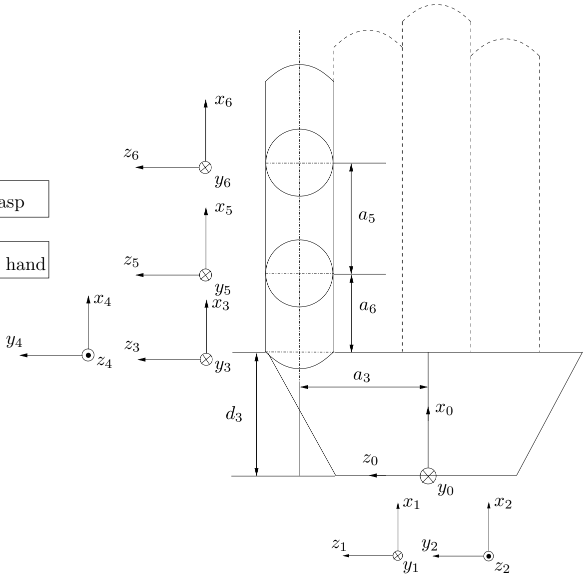

Fig. 4. Joint Coordinate of Little Finger

Consequently, we know that the coordinate transformation matrixes for each joint can be written as follows (with $T(i-1,i)$ denotes the transforamtion matrix from joint $i-1$ to joint $i$):

$$T(0,1) = \begin{bmatrix} \cos\theta_1 & \sin\theta_1 & 0 & 0 \\ -\sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$T(1,2) = \begin{bmatrix} \cos\theta_2 & 0 & \sin\theta_2 & 0 \\ -\sin\theta_2 & 0 & \cos\theta_2 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$T(2,3) = \begin{bmatrix} \cos\theta_3 & 0 & -\sin\theta_3 & -a_3\cos\theta_3 \\ -\sin\theta_3 & 0 & -\cos\theta_3 & a_3\sin\theta_3 \\ 0 & 1 & 0 & -d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

$$T(3,4) = \begin{bmatrix} \cos\theta_4 & 0 & -\sin\theta_4 & 0 \\ -\sin\theta_4 & 0 & \cos\theta_4 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

$$T(4,5) = \begin{bmatrix} \cos\theta_5 & 0 & -\sin\theta_5 & -a_5\cos\theta_5 \\ -\sin\theta_5 & 0 & -\cos\theta_5 & a_5\sin\theta_5 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

$$T(5,6) = \begin{bmatrix} \cos\theta_6 & 0 & -\sin\theta_6 & -a_6\cos\theta_6 \\ -\sin\theta_6 & 0 & -\cos\theta_6 & a_6\sin\theta_6 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

Therefore, the transformation matrix from palm to the root of the little finger is

$$T(0,3) = T(0,1)T(1,2)T(2,3) \quad (8)$$

The transformation matrix from the palm to the middle of the little finger is

$$T(0,5) = T(0,1)T(1,2)T(2,3)T(3,4)T(4,5) \quad (9)$$

The transformation matrix from the palm to the tip of the little finger is

$$T(0,6) = T(0,1)T(1,2)T(2,3)T(3,4)T(4,5)T(5,6) \quad (10)$$

## 4. MODELLING OF VIRTUAL OBJECTS AND VIRTUAL MANIPULATION ALGORITHM

In Section 2, a prototype for VM is proposed. In this section, some problems involved are briefly illustrated. Firstly, modelling of the DVO and VF are presented in Sections 4.1 and 4.2 respectively, then the kinetics of VO is presented in Section 4.3. Finally, stable grasp condition is proposed in Section 4.4.

### *4.1 Modelling of Dynamic Virtual Objects*

In the VM process, the motion of the virtual hand and the real hand should be the same. They are computed by the kinetics model of the virtual hand. On the other hand, the SVO will remain static in the virtual world. Therefore, only the DVO's position and status should be computed in the virtual space. The motion of the DVO is driven by the forces (such as gravity, the forces generated by other SVO and DVO) in the virtual space. In general, the following steps should be included in order to determine the state of a DVO:

- Firstly, the contact position, the normal force and the depth of the penetration between DVO and the virtual hand and/or the other VO should be determined.
- Based on the friction/spring coefficients of each object, the amplitude and the direction of the virtual contact force of each contact position should be computed.
- Then the dynamic equations for the DVO under gravity, virtual contact force and motion constrains can be obtained.
- Based on the stable grasp condition, determine whether the DVO is grasped by the virtual hand. The stable grasp condition consists of the force, the torque and the gesture equilibrium condition.
- If the DVO is grasped by the virtual hand, it should be fixed to the virtual hand, coordinate transformation should be carried out to compute the DVO (virtual hand)'s movement. Other wise, the DVO's dynamic behavior should be determined by its own kinetics equations.

### *4.2 Modelling of Virtual Force*

Considering the virtual forces on the contact point among different VO, they can be classified as force in the normal direction and friction in the tangent direction. The direction of the normal force is perpendicular to the plane of the contact point, the effect of this force is to resist the penetration of the models; the direction of friction is parallel to the plane of the contact point, it resists the reverse motions of different models.

Now, let us derive the model of VF. Let $X_1$ and $X_2$ represent two VO, noting their penetration forces as $N_1$ and $N_2$ respectively. The depth of the penetration is $d$. Elasticity coefficients of the two virtual objects are $k_1$ and $k_2$, the penetration depth in $X_1$ is $d_1$ and in $X_2$ is $d_2$. Therefore, we have $d = d_1 + d_2$, $N_1 = k_1 \cdot d_1$ and $N_2 = k_2 \cdot d_2$. Because the $N_1$ and $N_2$ are force and counterforce, we know that

$$N_1 = N_2 \quad (11)$$

then we can obtain

$$d_1 = \frac{k_2}{k_1 + k_2} \cdot d \quad (12)$$

Therefore, we can obtain the penetration force of $X_1$ is

$$N_1 = \frac{k_1 k_2}{k_1 + k_2} \cdot d \quad (13)$$

Similarly, we know that the penetration force of $X_2$ is

$$N_2 = N_1 = \frac{k_1 k_2}{k_1 + k_2} \cdot d \quad (14)$$

Besides the penetration force, friction is another kind of contact force. Normally, friction is classified as dynamic friction and static friction. If there is relative motion in the contact surface of two objects, the friction is called dynamic friction. Otherwise, it is called static friction. For the dynamic friction, it can be further classified as sliding friction and rolling friction. In this paper, we only consider sliding friction.

Assuming the position vector of contact point $i$ of virtual object $X$ is denoted as $\boldsymbol{x}_t^i$ at time instant $t$. We know that the velocity of the contact point at time instant $t$ is

$$\boldsymbol{v}_t^i = \frac{\boldsymbol{x}_t^i - \boldsymbol{x}_{t-1}^i}{\triangle t} \quad (15)$$

If $\|\boldsymbol{v}_t^i\| \geq \epsilon$ with $\epsilon$ being a small positive constant, the friction on that contact point is dynamic friction, otherwise it is static friction. The direction of the friction is the same to the direction of vector $\boldsymbol{x}_t^i - \boldsymbol{x}_{t-1}^i$. We know that the static friction $f_s$ should be

$$f_s \leq u_s \cdot N \tag{16}$$

and the dynamic friction $f_d$ should be

$$f_d \leq u_d \cdot N \tag{17}$$

with $u_s$, $u_d$ and $N$ denote the static friction coefficient, the dynamic friction coefficient and the penetration force respectively. Therefore, for a DVO, if there are $n$ contact points, denote the contact forces of the $i$th $(i = 1, 2, \ldots, n)$ contact point as $N_i$ and $f_i$ ($f_i$ is $f_{s_i}$ or $f_{d_i}$), noting the effect of gravity $(mg)$, the sum of external forces is

$$\sum_{i=1}^{n} \boldsymbol{F}_i = \sum_{i=1}^{n} N_i \cdot \boldsymbol{n}_i^0 + \sum_{i=1}^{n} f_i \cdot \boldsymbol{\tau}_i^0 + m \cdot \boldsymbol{g} \tag{18}$$

and the sum of the torques is

$$\sum_{i=1}^{n} \boldsymbol{M}_i = \sum_{i=1}^{n} N_i \cdot \boldsymbol{n}_i^0 \times \boldsymbol{r}_i + \sum_{i=1}^{n} f_i \cdot \boldsymbol{\tau}_i^0 \times \boldsymbol{r}_i \tag{19}$$

with $\boldsymbol{n}_i^0$ denotes the unit normal vector of the contact surface, $\boldsymbol{\tau}_i^0$ denotes the unit tangent vector of the contact surface and $\boldsymbol{r}_i$ is the radial vector from the contact point to the centroid.

### *4.3 Motion of the Virtual Object*

Currently, in the analysis of the motion of virtual object, normally only gravity and normal force are considered, probably due to the intervention of friction would greatly increase the complexity of the analysis. However, considering that friction plays an important role in the real world, in this paper, we will discuss the effect of friction. For clarity, only sliding friction is considered here.

Assuming at time instant $t_{t-1}$, the velocity of the virtual object is $v_{t-1}$, and the angular velocity is $\omega_{t-1}$. In the period $\triangle t = t_t - t_{t-1}$ the increments from $t_{t-1}$ to $t_t$ are $\triangle v$ and $\triangle \omega$. We have

$$\sum_{i=1}^{n} F_i \cdot \triangle t = m \cdot \triangle v \tag{20}$$

$$\sum_{i=1}^{n} M_i \cdot \triangle t = I \cdot \triangle \omega \tag{21}$$

Therefore, the velocity and the angular velocity of the virtual object at time instant $t$ are

$$v_t = v_{t-1} + \triangle v \cdot \triangle t \tag{22}$$

$$\omega_t = \omega_{t-1} + \triangle \omega \cdot \triangle t \tag{23}$$

In order to compensate the delay in the system, the velocity at time instant $t_t$ is used to compute the displacement of the virtual object from $t_{t-1}$ to $t_t$. Therefore, the displacements in this period can be noted as

$$\triangle x = v_t \cdot \triangle t \tag{24}$$

$$\triangle \theta = \omega_t \cdot \triangle t \tag{25}$$

There is a prerequisite in the discussion of this subsection, the stable grasp condition is not hold. When the object is grasped by the virtual hand, i.e., the stable grasp condition holds, the virtual object would be fixed to the virtual hand and move with the virtual hand together. Now, through coordinate transformation, the motion of the virtual object can be determined.

The coordinates included in this procedure are

- world coordinate $O_g X_g Y_g Z_g$;
- measurement coordinate $O_m X_m Y_m Z_m$;
- hand coordinate $O_w X_w Y_w Z_w$;
- virtual object coordinate $O_o X_o Y_o Z_o$.

Once these coordinates have been defined, the motion of the virtual object can be deducted as follows.

Assuming at time instant $t$, the wrist sensor's output is $(x_w, y_w, z_w, \psi_w, \theta_w, \gamma_w)$, then, the transformation matrix which represent the transformation from hand $(O_w X_w Y_w Z_w)$ to the measurement coordinate $(O_m X_m Y_m Z_m)$ is

$$T_{wm} = \begin{bmatrix} R^{3\times 3}(\psi_w, \theta_w, \gamma_w) & \boldsymbol{p}_w \\ \boldsymbol{0} & \boldsymbol{1} \end{bmatrix} \tag{26}$$

with $\boldsymbol{p}_w = [x_w, y_w, z_w]^T$. The transformation matrix from $(O_m X_m Y_m Z_m)$ to $(O_g X_g Y_g Z_g)$ is denoted as $T_{mg}$. This matrix is a constant matrix that depends on the system initial conditions. Consequently, the transformation matrix which represents the transformation from hand coordinate $(O_w X_w Y_w Z_w)$ to world coordinate $(O_g X_g Y_g Z_g)$ is

$$T_{wg} = T_{wm} T_{mg} \tag{27}$$

Denote the transformation matrix from virtual object coordinate $(O_o X_o Y_o Z_o)$ to world coordinate $(O_g X_g Y_g Z_g)$ as $T_{og}$, it can be computed by the parameters obtained when the virtual object hasn't been grasped by the virtual hand. Therefore, under the stable grasp condition, the virtual object coordinate to the hand coordinate coordinate transformation matrix is

$$T_{ow}^s = T_{og}^s (T_{wg}^{-1})^s = T_{og}^s (T_{wm}^s T_{mg}^s)^{-1} \tag{28}$$

If the virtual object is grasped by the virtual hand in the consequent period, i.e., the stable grasp condition always holds, the transformation matrix $T_{ow}^s$ would be a constant matrix (the superscript denotes the stable grasp status). Therefore, the motion of the VO should be computed by $T_{ow}^s$, specifically, in stable grasp state, the transformation matrix from VO to the world coordinate is

$$T^s_{og} = T^s_{ow} T_{wg} = T^s_{og} (T^s_{wm} T^s_{mg})^{-1} T_{wm} T_{mg} \quad (29)$$

In the stable grasp period, if the status of the virtual object changes from stable to unstable, then the motion of the virtual object should be recomputed by the algorithm proposed for unstable grasp.

### *4.4 Stable Grasp Condition*

In this subsection, the stable grasp condition is developed. In the VM process, the virtual object switches between stable grasp state and instable grasp state. If the stable grasp condition is too restrict, the VO may switch between the stable state and the instable state frequently. It is very difficult for the whole system to converge. Considering the following reasons:

- The assumption that the virtual object is rigid body is inaccurate, and there are differences between the VF and the real force.
- In the virtual cockpit system we studied, there are no haptic and force feedback. The only feedback is the vision feedback. If VO is assumed to fully satisfy the force and torque equilibrium condition, it is very difficult for the VO to reach the stable grasp state.

we decided to relax the equilibrium condition in practical system construction, which speeds up the convergence of the system. The equilibrium conditions for stable grasp condition are

$$|\sum_{i=1}^{n} \boldsymbol{F}_i| = |\sum_{i=1}^{n} N_i \cdot \boldsymbol{n}_i^0 + \sum_{i=1}^{n} f_i \cdot \boldsymbol{\tau}_i^0 + m \cdot \boldsymbol{g}| \leq \xi \quad (30)$$

$$|\sum_{i=1}^{n} \boldsymbol{M}_i| = |\sum_{i=1}^{n} \boldsymbol{N}_i \cdot \boldsymbol{n}_i^0 \times \boldsymbol{r}_i + \sum_{i=1}^{n} f_i \cdot \boldsymbol{\tau}_i^0 \times \boldsymbol{r}_i| \leq \eta \quad (31)$$

However, in the practical experiment, after relax the equilibrium conditions, the penetration between VO and the virtual hand increases though the convergence is speeded. This greatly degrades the third dimension of the virtual cockpit system, especially when there is not only contact force between VO and the virtual hand but also contact forces among different VO. Therefore, besides the force and torque conditions in equations (30) and (31), another kind of constraint, the gesture constraint is introduced to solve this problem.

In this paper, the gesture refers to the relative position of the virtual hand (including fingers) with VO, it can be determined by the number of the contact points between the virtual hand and the VO, and angles between different normals in each contact point. In this paper, the gesture constraint is as follows:

- The number of the contact points of the virtual hand and the virtual objects is required to be greater than 2.
- Among these contact points, the thumb should be included, i.e., the thumb should keeps contact with the VO.
- The angles of the tapers between the thumb and each of the other fingers should be larger than the predefined threshold $\alpha_0$.

By trial and error, we take $\alpha_0 = 120°$. Therefore, the stable grasp condition in this paper is the combination of the two constraints discussed above.

## 5. CONCLUSION

In this paper, firstly a prototype for VM process in VR system is proposed, which is used in a virtual cockpit system. Several problems involved in the VM process are briefly discussed, these problems include the modelling of virtual hand, modelling of VO, modelling of VF and kinetics analysis of VO, etc.

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