Grasping and Manipulation in Virtual Environment Using 3By6 Finger Device

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Abstract— **Realistic simulation of grasping requires accurate modeling of forces and torques on the virtual object resulting from the fingers in contact. We present isometric 3By6 Finger Device for multi-fingered grasping in virtual environment (VE). The finger device was designed to measure forces of three fingers. Model of grasping adopted from the analysis of multi-fingered robot hands was used. The virtual object corresponded dynamically to the forces and torques applied by the three fingers. The multi-fingered grasping is demonstrated in four tasks aimed at the rehabilitation of the upper extremities of stroke patients. The tasks include opening of a safe, filling and pouring water from a glass, training of muscle strength with an elastic torus and force-tracking task.**

I. Introduction

INTERACTION with objects in virtual environments (VE) through grasping and manipulation is an important feature of the future virtual reality (VR) simulations [1]. The interaction using the hand is possible by pushing, pulling or grasping the object to change its position, orientation or geometry. Realistic grasping is achieved through accurate modeling of the forces and torques at the VR object surface. The model of multi-fingered grasping can be adopted from the analysis of multi-fingered robotic hands [2].

In many VR applications instrumented gloves are used to manipulate and interact with virtual objects. The gloves provide information on the position of the fingers while no data on the grasping forces in VR world are collected [3]. Interaction with the VR gloves can be further enhanced by a haptic interface which provides active force feedback to the user. Multi-fingered haptic devices used in the VR include Rutgers Master II [4] and the exoskeleton device CyberGraps (Immersion Corporation, San Jose, CA). Haptic feedback can be partially replaced by a low-cost alternative such as visual force feedback [5] where the haptic information is simulated through visual cues presented to the user. When using isometric devices the motion of the fingers is constrained while the force applied to the force sensing elements is measured. If the visual feedback requires an increase of the active force, the user will apply higher force and consequently feel larger resistance due to the motion constraint, providing in this way an illusion of a tactile feedback [6]. The inherent drawback of the isometric input devices is inability to provide active feedback.

In this paper we present 3By6 Finger Device which was designed to accurately assess the fingertip forces and torques of three fingers. When using the device the movement of the hand and fingers is fully constrained allowing the VE to simulate grasping through the fingertip forces. The user can exert forces and torques which would normally be applied during grasping and manipulation in real environment. The 3By6 Finger Device was applied in the virtual environment for rehabilitation of hand function after stroke. Previous studies have shown beneficial effect of VR training to the rehabilitation of the upper extremities [7],[8]. In the paper we present the concept of multi-fingered grasping and describe four different VR training tasks aimed to improve multi-fingered force coordination.

II. Materials and Methods

A. 3By6 Finger Device

The 3By6 finger device was designed to simultaneously measure forces and torques applied by the thumb, index and middle finger. The device consists of three force/torque measuring sensors (50M31A-I25; JR3, Inc., Woodland, USA) located on the outer side of the hand (Fig. 1). The sensors are mounted on the aluminum construction, which provides firm support for the sensors during the

Fig.1. Finger device for the input of fingertip forces for multi-fingered grasping in virtual reality.

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measurement. The measurement range of the sensors is 150 N for the lateral forces and 300 N in the axial direction with the torque range of 8 Nm. The approximate outer measures of the finger device are 225x100x160 mm and total weight is 1.8 kg. During the measurement the hand is positioned between the thumb sensor and the two sensors for the index and middle finger. Finger fixations are used to fix the fingers and thumb in the correct configuration while providing transfer of forces and torques to the sensors. The fingers are attached to the support using Velcro straps. The device can be used either for the left or the right hand use by changing the orientation of the sensor platform by 180˚. The data acquisition from the three sensors is performed through a PCI receiver/processor board with the sampling frequency of 100 Hz. The data are filtered in real time using on-board integrated filter with the cut-off frequency of 32.25 Hz and delay of approximately 32 ms.

B. Mathematical Model of Grasping

Grasping in the virtual environment was described by the mathematical model adopted from the analysis of multi-fingered robot hands presented by Murray et al. [2]. To describe the interaction of a multi-fingered hand with an object, a mapping between the fingertip forces and the resultant wrench on the object with regard to the center of mass are needed. In our model of grasping we assume that the location of the fingers, when in contact with the object, is fixed. The location of the *i*-th contact point is defined by the coordinate system C_i with the *z*-axis pointing inwards to the object surface (Fig. 2). The position and orientation of the contact coordinate system are described by the vector $p_{oci} \in \Re^3$ and the rotational matrix $R_{oci} \in \Re^{3\times 3}$, respectively. The force applied at the contact point is defined by the contact wrench $F_{Ci} \in \Re^6$. The type of contact is described by the corresponding wrench basis $B_{Ci} \in \Re^{6\times p}$ defining the number of degrees of freedom *p* of the contact. In case of point contact with friction follows:

$$F_{C_i} = B_{C_i} \cdot f_{C_i} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}^{\mathrm{T}} \cdot f_{C_i} \qquad (1)$$

The vector $f_{Ci} \in \Re^{p}$ describes the forces and torques applied by the fingers which correspond to the Coloumb friction model.

The effect of each fingertip force on the object is described by the contact map $G_i \in \Re^{6\times p}$:

$$F_{OC_i} = \begin{bmatrix} R_{OC_i} & 0 \\ P_{OC_i} & R_{OC_i} \end{bmatrix} \cdot B_{C_i} \cdot f_{C_i} = G_i \cdot f_{C_i} \qquad (2)$$

The matrix P_{OCi} gives representation of vector p_{OCi} as the position of the contact point. The resulting wrench of *k* fingers is described by the sum of contributions from all the contact points, where matrix *G* represents the grasp map:

$$F_O = G_1 \cdot f_{C_1} + G_2 \cdot f_{C_2} + \ldots + G_k \cdot f_{C_k} = G \cdot f_C \qquad (3)$$

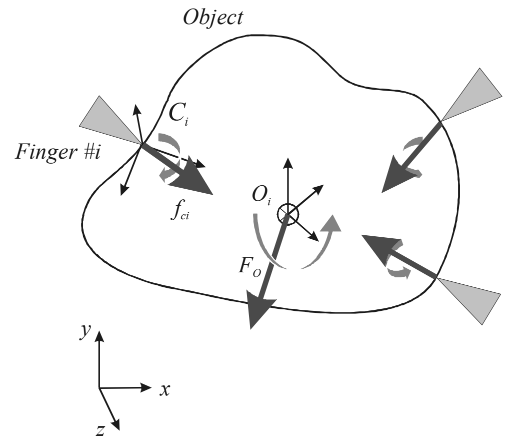

Fig.2. Model of multi-fingered grasping of a rigid object.

C. Mathematical Model of Object Dynamics

For realistic interaction with objects in virtual environment mathematical model of body dynamics that is under consideration is needed. The model describes kinematic variables based on the force and torque with respect to the center of mass. To allow high flexibility of the dynamics model, the virtual object is in its center of mass suspended on a virtual spring with friction in all six DOF (i.e. three translations and three rotations). By adjusting the coefficients, different dynamic behavior of the object is achieved, allowing high flexibility of the environment. The number of active DOF can be limited to restrict the movement in particular directions (e.g. a knob must only rotate around its main axis; other five DOF are constrained). The physical model of the object incorporates the object mass, inertia, basic shape (e.g. sphere, cylinder) and the location of its center of mass in the global coordinate system.

To describe body dynamics in the local coordinates we used Newton-Euler equations written in the matrix form as follows [12]:

$$M \cdot \ddot{x} + C \cdot \dot{x} + N \cdot x + g = F_O \qquad (4)$$

$x \in \Re^6$ represents the vector of local coordinates describing the object location, the matrix $M \in \Re^{6\times 6}$ is the inertia matrix consisting of object mass and inertia parameters, $C \in \Re^{6\times 6}$ is a diagonal matrix of friction coefficients, $N \in \Re^{6\times 6}$ is a diagonal matrix of stiffness coefficients and $g \in \Re^6$ is the gravity vector. F_O is the total wrench on the object derived from the equation (3) of the model for multi-fingered grasping.

The acceleration vector is expressed and integrated into:

$$x = \iint \ddot{x} = \iint M^{-1}(F_O - C \cdot \dot{x} - N \cdot x) \qquad (5)$$

Equation (5) describes the dynamic behavior of the virtual object in space and time resulting from the total wrench on the object, its physical properties and given environmental variables.

D. Grasping in Virtual Environment

The visualization of the VE was achieved using open source VR system MAVERIK (Advanced Interfaces Group, The University of Manchester, UK) based on OpenGL. MAVERIK engine was selected due to its high performance and high-flexibility of the VR environment [9]. Two C-libraries were programmed to include the mathematical models of the environment and grasping, independent of the visualization engine. The rendering loop allows the update of data acquisition and visualization with the frequency of 100 Hz. Three symbolic virtual fingers shown as geometric cones represent the location of each contact at the object surface. When a threshold force is exceeded, the virtual finger is moved along its axis proportionally to the applied force until the collision with the object surface. The object is grasped when two or three fingers in opposition are in contact with the object. The total force and torque on the object are determined from the kinematics of grasping described in (3) while the effect of the total wrench on the object is defined by (5). Constraints can be implemented to restrict the movement of the object in selected directions. The dynamic parameters of stiffness and friction can be controlled for each DOF to achieve flexible behavior of the object.

III. Results

For the rehabilitation in the VE four tasks were designed with the aim to increase the grip force coordination and grip strength by repetitive training (Fig. 3). Due to the limited space only short description of the tasks and example of output results will be given. More details on the VE will be presented in our subsequent publications.

A. VR Task: Open the Safe

In the first task the user is required to open the door of a safe by unlocking the combination code (Fig. 3a). The combination code is presented on the screen and the user has to rotate sequentially the knob to the correct values. The code is randomly generated in each session. The knob of the safe is marked with numbers from *1* to *7* on the right side and letters from *A* to *F* on the left side. The neutral position of the knob is denoted with *0*. When the knob is turned to the correct orientation, the current symbol of the combination code disappears and the user has to find the next symbol of the combination. The user has to first grasp the knob by applying force in the axial direction and then apply axial torque to turn it to the correct orientation. The task is completed when the user "cracks" all the symbols of the presented combination code and the safe door open.

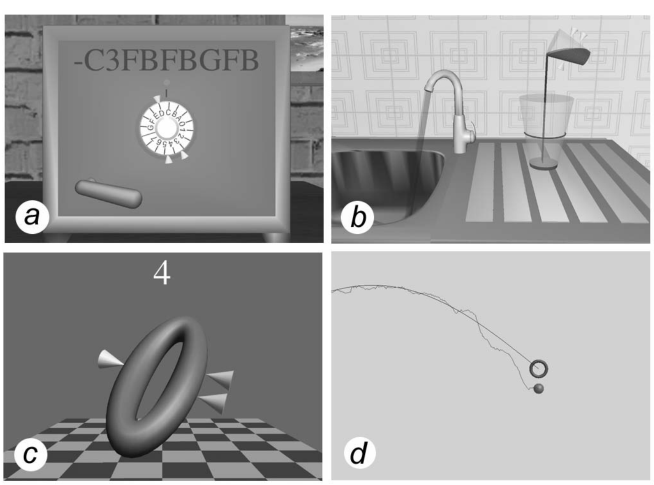

Fig.3. VR tasks for rehabilitation of hand function in virtual environment: (a) Open the safe, (b) Fill the jar, (c) Elastic torus, (d) Tracking

B. VR Task: Fill the Jar

The second task shows a scene from a kitchen, where the user has to fill an empty jar with water (Fig. 3b). The task requires the user to grasp the empty glass, transport it and fill it with water from the kitchen sink, and then pour the water into the jar. The task is completed when the jar is filled to the level marked with a red line on the side of the jar. The glass is grasped by applying opposing force with two or three fingers. The glass can be moved in either direction by applying resulting force of all fingers into the corresponding direction while the object is securely grasped. The movement is restricted to the x-y (vertical) plane and the rotation is allowed only around the z-axis. Basic collision detection with bounding boxes and collision rays is implemented. The glass is moved under the water flow to fill the glass with water. The dynamics of water inside the glass during movement is modeled by a cone shaped body, which corresponds to tilting and reduction of water height when the water is poured out. The dynamic behavior of the glass changes as the glass is filled with water and mass is increased. The difficulty of the task can be adjusted by changing the dynamics parameters of the glass and by setting different target levels for the jar.

Figure 4 (above) shows the fingertip force data exerted on the glass during the first sequence of the task (i.e. lifting the glass, filling it with water and pouring water into the jar). While the object is grasped the normal force of the three fingers (F_z) is positive, while the lateral forces influence the tilting of the object. The orientation of the object is kept around zero degree during the transfer phase while the user is trying to keep the orientation of the glass stabile. When pouring the water into the jar, the orientation angle is slowly increasing to 90 degrees while the lateral forces of the fingertip are also increased.

C. VR Task: Elastic Torus

The third task is aimed to increase the grip strength by repetitive exercises of hand opening and closing (Fig. 3c). The patient is presented with a deformable torus with geometry and dynamical model corresponding to the total force between the fingers in contact. The position of the torus is fixed in space. The softness of the torus can be adjusted to abilities of each individual. Global deformation modeling was used to model the softness of the torus in the

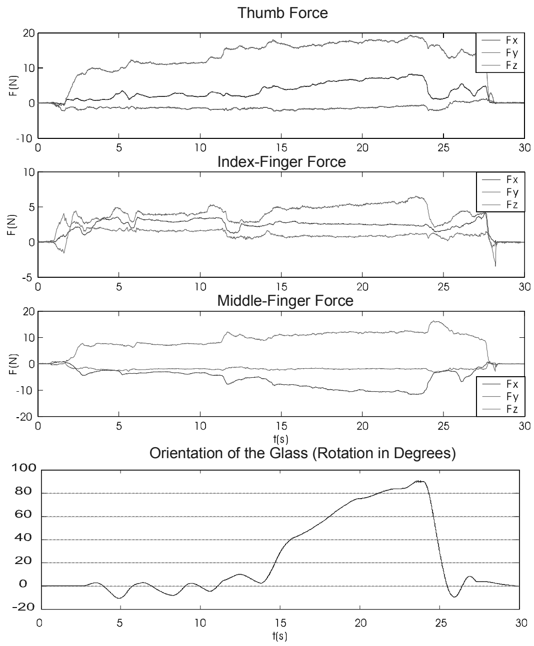

Fig.4. Fingertip forces and orientation angle of the glass during one sequence of the task (i.e. lifting the glass, filling it with water and pouring water into the jar)

VE [10]. When the torus is compressed beyond the required degree, the color of the object is changed from dark blue to purple, indicating the user to retain the grip. When the grip is opened again, the color is changed back to purple. The counter on the screen indicates the number of successfully performed sequences. The difficulty of the task can be adjusted by changing the softness of the torus, selecting the required number of cycles and the required time delay between the opening and closing of the hand. The force results can be used to evaluate the grip strength and muscle fatigue during training.

D. *VR Task: Tracking*

The fourth task is intended mainly for the assessment of the overall training process (Fig. 3d). The results of previous studies [11] have demonstrated the use of tracking tasks for the evaluation and training of grip force control. In the tracking task a person applies the force according to the visual feedback, while trying to minimize the difference between the static or moving target and the actual response. The target signal is presented with a blue torus moving vertically in the center of the screen and the applied force is indicated with a red semi-transparent sphere. When the grip force is applied, the red sphere moves upwards and when the grip is released, the sphere moves to the initial position. The performance measure of the task is evaluated by calculating the root mean square error between the target signal and the measured response.

IV. CONCLUSIONS

In this paper we presented a new approach to multi-fingered grasping and manipulation in virtual environment using dedicated isometric input device. The 6by3 Finger Device developed allows accurate measurement of fingertip forces and torques and provides sufficient information for accurate simulation of grasping of objects in VR. Fully controllable and flexible physics of the VE was implemented to simulate dynamic behavior of the manipulated objects. The developed VR grasping library allows simulation of different means of interaction using force input from the multi-fingered contacts.

In the paper we presented four VR application intended for rehabilitation of hand function. The tasks are aimed to assess and promote grip force control and grip strength through functional activity, while being fun and motivating for the patient. The tasks were designed to provide realistic experience while minimizing the load on the cognitive perception. In our future work the presented virtual rehabilitation environment and the finger device will be applied as a training method in a group of patients after stroke.

The 3By6 Finger Device was primarily designed and is used for measurements of stroke patient upper extremity within European Union (EU) funded project Alladin. Larger scale study is underway. Further improvements can be made in the design of the hardware to include more cost-efficient sensors and less degrees of freedom. The input device could be redesigned to the specific tasks in rehabilitation therapy.

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