

5-Finger Exoskeleton for Assembly Training in Augmented Reality

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Abstract. This paper proposes an augmented reality based exoskeleton for virtual object assembly training. This proposed hand exoskeleton consists of 9 DOF joints which can provide force feedback to all 5 fingers at the same time. This device has ability to simulate shape, size, and weight of the virtual objects. In this augmented reality system, user can assembly virtual objects in real workspace which is superimposed with computer graphics information. During virtual object assembly training, user can receive force feedback which is synchronized with physics simulation. Since this proposed system can provide both visual and kinesthesia senses, it will help the users to improve their assembly skills effectively.

Keywords: Exoskeleton Device, Augment Reality, Force Feedback.

1 Introduction

In general, object assembly training requires several resources such as materials, equipment, and trainers. The simulation is one of training solutions which can save costs, times, and damages occurred during training. However, most of simulators do not provide sufficient realistics and senses. Hence, this paper proposes an augmented reality based exoskeleton for virtual object assembly training. This system can provide more realistics and senses such as visual and haptic during operation. Objects for assembling task are simulated in the form of computer graphics superimposed on the real environment. Furthermore, this system can provide force feedback while the trainee assembles virtual objects.

Force feedback technology in general can be categorized into 2 styles which are wearable and non-wearable. The wearable force feedback devices are usually in the form of hand, arm, and whole body exoskeletons. The non-wearable force feedback devices are usually in the form of force feedback stylus, joystick, and small robot arm. Immersion CyberGrasp mounts a force feedback device and 3D tracking device on Immersion CyberGlove [1]. It uses cables to transfer power from motor to the exoskeleton device. This device is lightweight and its motors are mounted on its base separately. Koyama, T. proposed a hand exoskeleton for generating force

feedback [2]. This device uses the passive actuators, clutches, for simulating smooth force feedback. Bouzit, M. implemented small active pneumatic actuators for generating force feedback to a hand exoskeleton [3]. This exoskeleton has a small size and light weight. Ganesh Sankaranarayanan and Suzanne Weghorst proposed an augmented reality system with force feedback for teaching chemistry and molecular biology [4]. This system simulates the geometry and flexibility of organic compounds and then uses Phantom haptic device to create force feedback. Matt Adcock, Matthew Hutchins, and Chris Gunn used augmented reality with force feedback for designing, advising, and surveying among users [5]. This device uses pneumatic actuators for creating force feedback.

All previous non-wearable exoskeleton devices, which are implemented with haptic device and augment reality for generating force feedback to user, cannot simulate force feedback to each joint of hand. Hence, this paper proposes an augmented reality system using wearable hand exoskeleton for generating force feedback to user during virtual assembly task.

2 System Overview

Figure 1 shows the configuration of the proposed system. This system consists of a hand exoskeleton device which is used to generate force feedback to the user. The exoskeleton also sends finger's angles and receives braking angles from the main computer. Markers are used to track the positions and orientations of virtual objects and user's hand. Video camera is used to receive video image from the real environment. Camera is mounted on LCD Glasses Display which is used to show the graphics in the same view of user's. Graphics is updated by the physics engine using the Bullet software library [6].

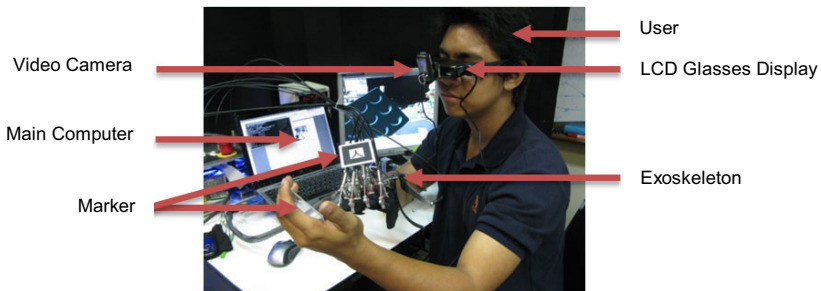


Fig. 1. System Overview

3 System Components

The system consists of two main components which are hardware and software components. Hardware includes an exoskeleton device with controller, an LCD

Glasses Display, a video camera, force sensors, and markers. Software includes graphics manager and vision manager.

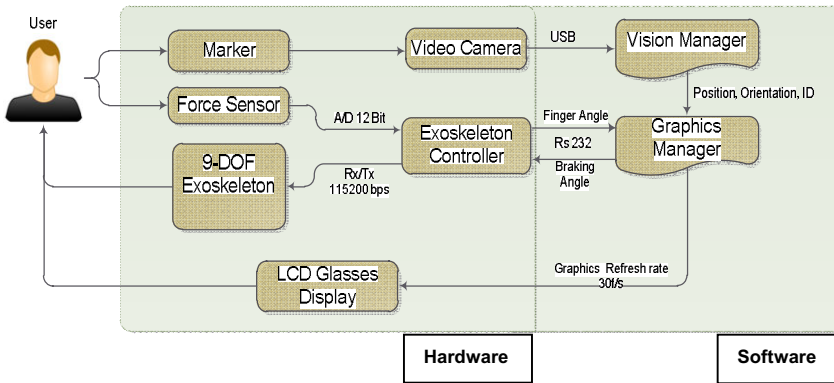


Fig. 2. System Components

In Figure 2, the system receives video image from the video camera, does image processing to find targets' positions and orientations, and generate computer graphics superimposed on video image. It also sends force feedback in form of braking angles to all motors on exoskeleton device.

3.1 Exoskeleton Device

Exoskeleton device is used to generate force feedback to a user. It receives commands from the main computer through the exoskeleton controller for controlling its motors. The controller also receives sensed forces from strain gages for adjusting tensions of the cables.

In general of object manipulation by hand, finger no.1 can rotate about X and Z axes but fingers no.2-5 can rotate only about Z axis. The last joint of each fingers no.2-5 cannot be controlled independently. Rotation of the last joint depends on the previous joint's rotation. Hence, mechanical structure of the proposed exoskeleton device is designed so that exoskeletons of fingers no.2-5 can generate 2-DOF force feedback at first joint and fingertip. To simplify the mechanical structure exoskeleton of finger no.1, this exoskeleton can generate only 1-DOF force feedback at the fingertip. Computer graphics of virtual finger no.1 and fingers no. 2-5 are designed with 2 DOFs and 3 DOFs, respectively as shown in Figure 3. In addition, the movements of virtual fingers are updated correspondingly to real finger's. Physics engine uses forward kinematics from Equation 1 to calculate the position and orientation of each finger from the D-H parameters as shown in Table 1 and 2 [7]. Since the last joints of all fingers always move relatively with the middle joints, inverse kinematics can be calculated by converting 2-DOF configuration to 1-DOF

configuration of finger no. 1 and 3-DOF configuration to 2-DOF configuration of fingers no. 2-5 as shown in Figure 4.

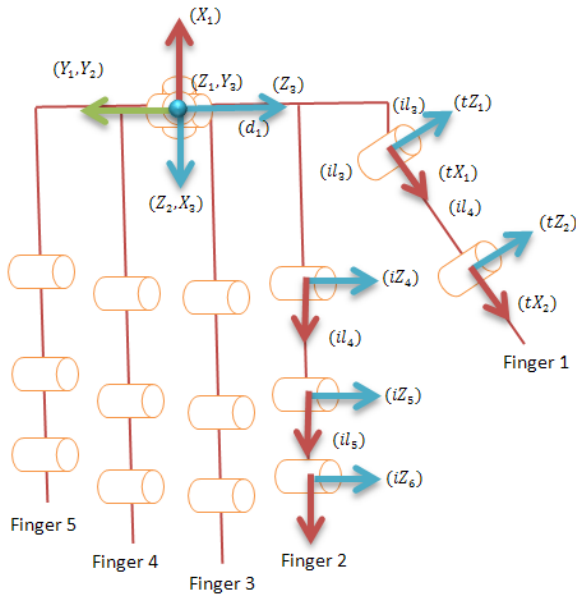


Fig. 3. Frames and axes of hand

Table 1. Finger no.1's DH-parameters

link	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	Offset	θ_1
2	90	0	0	θ_2
3	-90	0	0	θ_3
4	45	il_3	d_4	θ_4
5	0	il_4	0	θ_5

Table 2. Finger no.2-5's DH-parameters

link	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	Offset	θ_1
2	90	0	0	θ_2
3	-90	0	0	θ_3
4	0	il_3	d_4	θ_4
5	0	il_4	0	θ_5
6	0	il_5	0	θ_6

$${}^{i-1}T_i = \begin{bmatrix} \cos \theta_i & -\sin \theta_i & 0 & \alpha_{i-1} \\ \sin \theta_i \cos \alpha_{i-1} & \cos \theta_i \cos \alpha_{i-1} & -\sin \theta_i & -\sin \alpha_{i-1} d_i \\ \sin \theta_i \sin \alpha_{i-1} & \cos \theta_i \sin \alpha_{i-1} & \cos \theta_i & \cos \alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

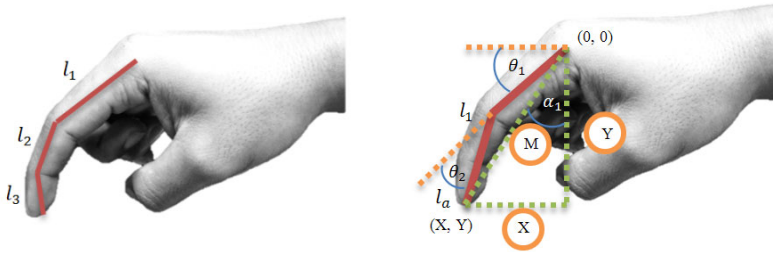


Fig. 4. Plane geometry associated with a finger

Equation 2 is used to calculate the distance from fingertip to base. Equation 3 is used to calculate the rotation angle of the fingertip with respect to the first joint. The first angle between base joint and middle joint can be obtained using the Equation 4-5. Equation 6 is used to find the second angle between middle joint and fingertip. Inverse kinematics is used to calculate the braking angle when a collision occurs.

$$M = \sqrt{x^2 + y^2} \tag{2}$$

$$\alpha_1 = \tan^{-1} \frac{y}{x} \tag{3}$$

$$l_a = \sqrt{(l_2^2 + l_3^2)} \tag{4}$$

$$\theta_1 = \alpha_1 - \cos^{-1} \left[\frac{l_a^2 - l_1^2 - M^2}{-2l_1M} \right] \tag{5}$$

$$\theta_2 = 180 - \cos^{-1} \left[\frac{M^2 - l_a^2 - l_1^2}{-2l_1l_a} \right] \tag{6}$$

Strain gage is mounted on each joint of the exoskeleton as shown in Figure 5-a. Strain gages are used to receive force which acts on each joint of exoskeleton. Nine digital servo motors in exoskeleton device are used to transfer force to the user by adjusting the cable's tension. Each digital servo motor with maximum torque at 8kg/cm is installed on its base separately from exoskeleton device as shown in Figure 6. The overview of exoskeleton system can be shown in Figure 7.

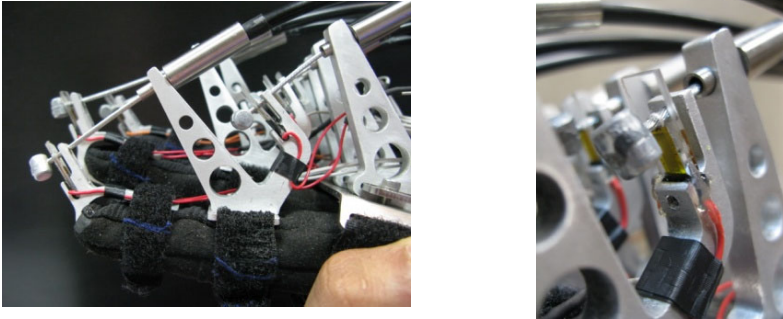


Fig. 5. (a) Strain gages mounted on the exoskeleton (b) Close-up view

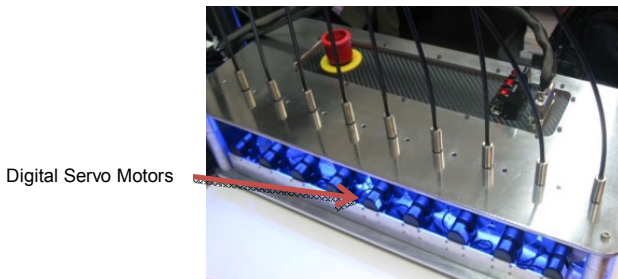


Fig. 6. Servo motors on exoskeleton's base

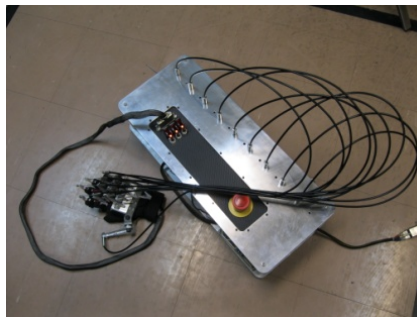


Fig. 7. Overview of exoskeleton system

Exoskeleton controller's MCU, which is STM32 ARM Cortex-M3 core-based family of microcontrollers, is for receiving 12 bit A/D data from each strain gage and controlling all motors. It can communicate with computer via serial port at 115,200bps and interface with motors via rx/tx pins. The main control loop is programmed to receive all force data from the 9 strain gages and braking angles for

motors from the main computer. If value of each strain gage is less than zero, each motor will pull the cable for adjusting the tension of cable. If value of each strain gage is more than zero and motor angle is less than the breaking angle, motor will release the cable motors. If motor angle is more than the breaking angle, each motor will hold its position. Exoskeleton controller also returns the motor angles to the main computer for updating graphics.

3.2 Vision Manager

The Logitech 2 MP Portable Webcam C905[8] is used to capture video image and send it to the main computer. This camera is mounted on LCD Glasses Display in order to synchronize between the user's view and camera's view. Video capture resolution is 640x480 pixels and graphics refresh rate is 30 frames per seconds as shown in Figure 8. The vision manager applies the ARToolkit software library [9] to locate markers and send the marker's position and orientation to the graphics manager.

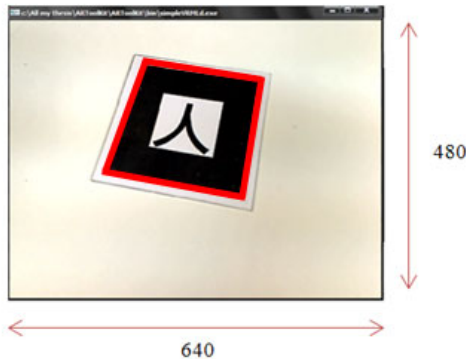


Fig. 8. Video Display

3.3 Graphics Manager

Graphics manager is responsible for rendering virtual objects and virtual hand on a marker using OpenGL as shown in Figure 9 (a) and (b). Bullet physics engine included in the graphics manager is used to detect collisions and calculate reaction force from virtual hand's manipulation. Virtual hand is a VRML-based model with separated link models. Angle of each finger read from the exoskeleton device is sent to the graphics manager via the serial communication. Position and orientation of each finger model can be calculated from forward kinematics explained in section 3.1. The calculated position and orientation are used to update virtual hand's position and orientation in physics simulation.

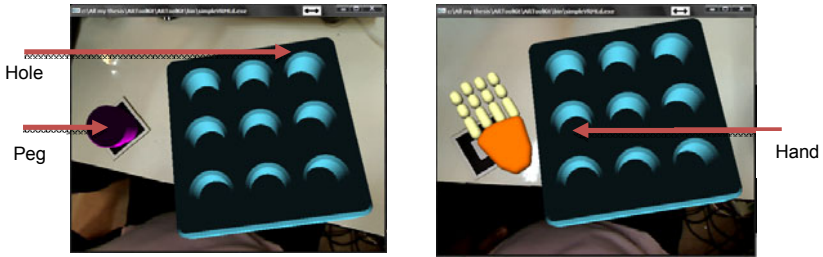


Fig. 9. (a) Virtual objects in physics simulation (b) Virtual hand in physics simulation

4 Experimental Results

4.1 Sensor Data Map

This experiment is set to explore the relationship between force and A/D data. First, strain gages are fixed on a piece of clear acrylics. Forces with range of 0-80 N are applied to the tip of acrylics as shown in Figure 5-b. The experimental results of force and corresponding A/D data are plotted in Figure 10.

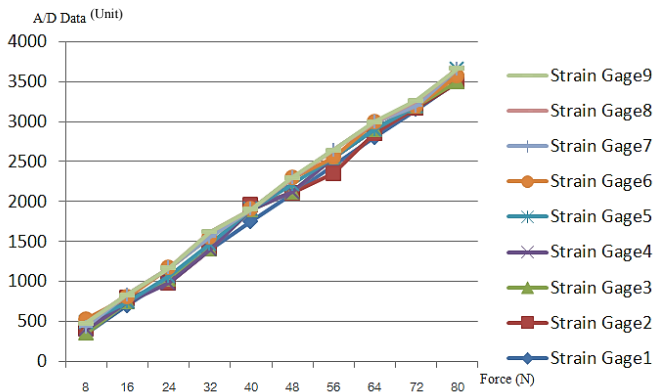


Fig. 10. Data mapping between force and A/D data

In Figure 10, the horizontal axis represents force applied to the strain gage and the vertical axis represents A/D data read from the exoskeleton controller. The results show that strain gage can return data in a linear fashion.

4.2 Maximum Force Feedback

This experiment is set to explore the maximum force feedback provided by the exoskeleton device. First, the user wears the exoskeleton to do grasping while the motors are set to hold their original positions. The exoskeleton controller then queries the maximum forced from strain gaged.

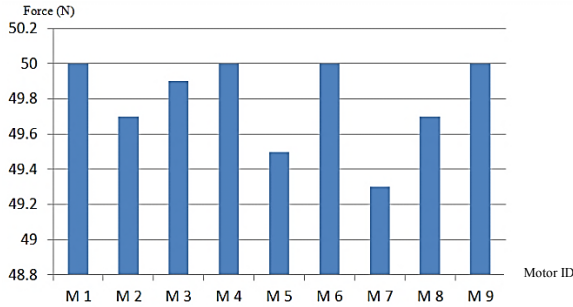
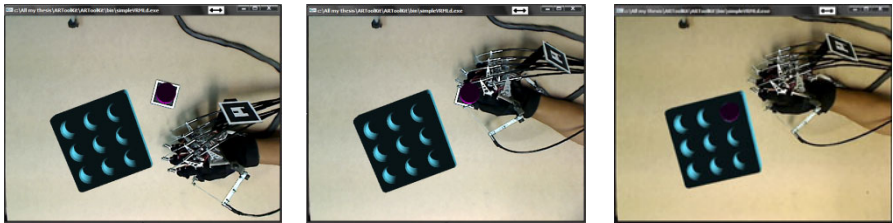


Fig. 11. Maximum force feedback from motors

In Figure 11, the horizontal axis represents motor IDs and the vertical axis represents forces exerted on each joint. The results show that exoskeleton device can generate maximum force feedback up to 50 N.

4.3 Virtual Assembly Task

This experiment is set to test the virtual object assembly task. In this experiment, the user is allowed to use the proposed exoskeleton device to manipulate the virtual objects in the real environment. The goal of this virtual assembly task is to put virtual pegs in holes with force feedback effect. All virtual objects with physics simulation are augmented on the real markers as shown in Figure 12-a. User can receive force feedback while he/she manipulates the virtual objects as shown in Figure 12-b.



(a) Before grasping virtual object (b) Grasping virtual object (c) Virtual object in the hole

Fig. 12. Virtual assembly task with force feedback

Figure 12-c shows the completion of one virtual peg assembled in to hole. This operation can be applied for training the user in more complex assembly task with augmented information. Furthermore, the graphics refresh rate is about 25 frames per seconds.

5 Conclusions and Future Works

This research proposed an augment reality with force feedback system for virtual object assembly task. Exoskeleton device was designed and built to generate 9-DOF

force feedback to the user's hand. It can generate with maximum forces up to 5N for each finger. Virtual objects in physics simulation can be superimposed on the tracked real markers. Graphics refresh rate is about 25 frames per seconds. Several assembly trainings can be applied using this proposed system. In the training, the user can use the hand exoskeleton to manipulate virtual objects with force feedback in the real environment. This provides more realistic and improves the training performances.

Future works of this research would cover virtual soft object manipulation, enhanced graphics user interface, and markerless augmented reality implementation.

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