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ORIGINAL PAPER

Design of a haptic system for medical image manipulation using augmented reality

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Abstract

This work discusses the development of an augmented reality (AR) interface that allows users to manipulate 3D anatomical structures (segmented and reconstructed from real medical studies) through haptic interactions by means of a five-degrees-of-freedom hand-exoskeleton. The exoskeleton allows the hand to move throughout its nominal range of motion. Our interface allows users to manipulate virtual objects more naturally thanks to its three points of contact, unlike most commercial haptic systems, which only have one point of contact. The preliminary results indicated a proper 3D segmentation and reconstruction of the anatomical structures of interest, as well as an adequate interaction between the haptic exoskeleton and the AR interface.

Keywords Augmented reality · Exoskeleton · Haptic system · Medical imaging segmentation

1 Introduction

Any type of haptic interaction (e.g. holding, pushing, or touching an object) in a virtual environment depends on a robotic system to provide force feedback to users [1]. In industrial contexts, traditional employee training is performed using real equipment or parts thereof; however, this strategy may lead to drawbacks such as high costs or equipment damage. Moreover, in some particular areas, such as aviation or medical surgery, it is impossible for trainees to use the real equipment and for trainers to predict all the real scenarios [2]. As a result, multiple computer solutions are developed as low-cost, adaptable training alternatives. Virtual reality (VR) and AR technologies allow to simulate complex work environments (composed of any kind of scenario, tool and equipment) by means of computer graphics and machine vision [2].

AR interfaces typically involve the overlay of virtual images in the real world. The goal is to blend reality and virtuality in a seamless manner. While great advances have been made in AR display technologies and tracking techniques, just a few systems provide tools that let users interact with and modify AR content. Furthermore, even basic interaction tasks, such as manipulation, copying, annotating, and deleting virtual objects, have often been poorly approached [3].

Several research groups have developed systems that combine AR and haptic technologies [3, 4]. For instance, in [3] the authors proposed a technique for natural interaction with virtual objects in AR environments. The technique relies on image processing software and markers to be placed on the fingers and the hand to track user gestures, and it is combined with haptic feedback devices to help users feel virtual objects. Similarly, the authors of [4] proposed an AR-based hand exoskeleton for virtual object assembly raining, which can simulate the shape, size, and weight of virtual objects.

In this context, this research proposes an AR-based haptic interface that allows users virtually touch anatomical structures (3D representations of real anatomical structures created from medical images), in order to create an educational and/or training tool for surgeons or physicians. Because the use of AR allows virtual anatomical structures to be superimposed on real scenarios (e.g, operating theaters).

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2 Methodology

2.1 Medical images datasets

We used images from two datasets and a clinical study of cranial computed tomography (CT). The first dataset included chest CT scan images (475 × 335 × 123 voxels and voxel size 0.98 mm × 0.90 mm × 2.0 mm) acquired by the Léon Bérard Cancer Center and the Biomedical Imaging Research Laboratory (CREATIS Lab) [5] in Lyon, France. The second set consisted of magnetic resonance images (MRI) from a brain (181 × 217 × 181 voxels and voxel size 1 mm × 1 mm × 1 mm), retrieved from the BrainWeb database [6]. Finally, we used a cranial region CT scan image (512 × 512 × 96 voxels and voxel size 0.48 mm × 0.48 mm × 1.27 mm) from a real clinical study.

2.2 Segmentation and 3D reconstruction of anatomical structures of interest

To perform the segmentation of medical images, we implemented the Chan-Vese algorithm [7] using Matlab R2017b. The Chan-Vese algorithm is an active contour-based method, and it is particularly useful in the segmentation of medical images due to its robustness with respect to noise. Moreover, it is able to detect and represent complex topologies and automatically detect interior contours [8].

The previously described images were segmented bidimensionally by means of the iterative algorithm presented in [7], starting from the temporal evolution of an energy functional. Subsequently, we wrote a Matlab script to perform the segmentation of each image. In the first data set (chest CT scan), the lungs were segmented; in the second study (cranial CT), the skull was segmented; and finally, for the third set of data (brain MRI), we segmented brain white matter. The result of this process is a VTP file (Visualization Toolkit Polygonal Data) of each structure of interest, which contains information of the vertices forming the surface to be reconstructed. We generated the VTP files from a volumetric data using the VTK libraries. Once we obtained the anatomical region of interest (A-ROI) from the medical images, we performed 3D reconstruction of the A-ROI with VTK library functions [9]. Then, we stored the resulting 3D reconstruction data in an OBJ file.

2.3 Augmented reality system

We saved the reconstruction data in an OBJ file, since this format is compatible with Unity, a cross-platform game engine that uses the C# programming language. Moreover, Unity is compatible with Metavision's Meta 1 AR glasses, which include an RGB camera and an infrared proximity sensor to detect movement in the upper extremities (i.e. hand, finger, and fist), used as a reference point to locate virtual components. The interaction between Unity and the Meta 1 glasses allows experts to create AR objects and modify their attributes using the MetaBody class (included in the SDK of Meta 1). For instance, objects can be rotated, resized, placed on a defined marker, or moved within the visual field [10].

Since the OBJ file stored the coordinates of the vertices to render a volumetric object, it is possible to create a mesh structure in Unity. A mesh uses arrays to represent vertices, triangles, normals, and texture coordinates, which is useful information to know when an object collides with the mesh; that is, when an object matches or surpasses the location of the mesh. As the following step, we created the mesh of each of the three previously reconstructed anatomical structures. Additionally, we programed a C# script to detect when the end effector collided with the mesh of the structures.

The AR interface comprises three different scenarios, in which the three previously reconstructed 3D structures are shown. We set different stiffness values, depending on the deformation property of each segmented anatomical structure.

2.4 Exoskeleton

We designed an exoskeleton to manipulate the anatomical structures of the AR system and achieve the haptic sensation. This robotic system enables the independent movement of three kinematic chains: the thumb finger (with one degree of freedom in the metacarpophalangeal joint), the index finger (with two degrees of freedom to move the proximal and middle phalanges), and the remaining three fingers together (also with two degrees of freedom to move the proximal and middle phalanges). This design allows users to make complex movements, similar to exoskeletons reported in the literature [11, 12]. The exoskeleton pieces were designed using SolidWorks 2015. The mechanical structure is composed of three main mechanisms: Mechanism A controls the movement of the little, ring and middle fingers, whereas Mechanism B is responsible for the movement of the index finger. Finally, thumb movements are controlled by Mechanism C, which in turn is formed by two pieces: a piece where the thumb is mounted and a base where the actuator is placed. Additionally, we designed a piece to link mechanisms A and B in the dorsal side of hand. Figure 1 depicts the assembly of all the exoskeleton pieces.

To control the movements of the mechanisms, we used five DC actuators and five position sensors (encoders), both from Pololu Robotics and Electronics. These actuators and sensors which are small and suitable for controlling the exoskeleton.

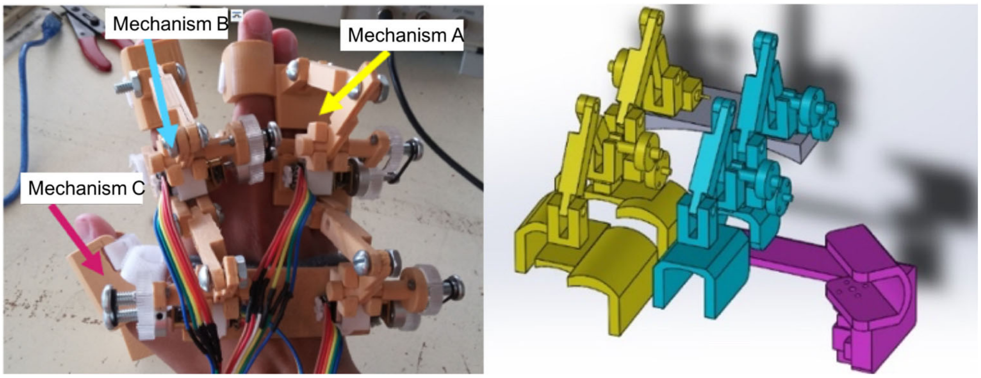

Fig. 1 Design of the hand exoskeleton [Mechanism A (yellow), Mechanism B (blue), and Mechanism C (pink)]

2.5 Haptic system integration

To control the exoskeleton we used an Arduino Mega 2560 board running at 1kHz. The first step in the control loop is to measure the position of each of the motors through the encoders. These readings are then sent to the AR visual interface through the serial port, where the position of the endpoint of mechanisms A and B is calculated by means of the direct kinematics given by

$$H = \begin{pmatrix} 1 & 0 & 0 & d_x \\ 0 & \cos(q_1+q_2) & -\sin(q_1+q_2) & d_y - l_1\sin(q_1) - l_2\sin(q_1+q_2) \\ 0 & \sin(q_1+q_2) & \cos(q_1+q_2) & d_z + l_1\cos(q_1) + l_2\cos(q_1+q_2) \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (1)$$

where H is an homogeneous transformation matrix representing the direct kinematic model, q_1 and q_2 are the rotation angles of the links, l_1 and l_2 are the link lengths of the exoskeleton, and (d_x, d_y, d_z) correspond to the translation coordinates from the origin (on the dorsal surface of hand) to the metacarpophalangeal joints. For Mechanism C, which has only one link, direct kinematics is obtained using the Pythagorean theorem.

In the visual interface, we compared the positions of the endpoints of each mechanism with the location of mesh of the virtual anatomical structures. Specifically, we looked for interaction (collisions) between the hand and the virtual object. When interaction was detected, we measured the distance between the virtual object surface and the position of the end-effector of the corresponding mechanism was in direction of the geometric center of the object (see Fig. 2). Then, the reaction force using Hooke's law equation as follows:

$$F = Kx \quad (2)$$

where K represents the stiffness (elasticity factor) of the virtual object, and x is the displacement (measured deformation).

In Fig. 2, r represents the radius of the sphere (i.e. distance between the center of the structure and its surface), and d is defined by

$$d = x_c - x_e \quad (3)$$

where x_c is the centroid of structure and x_e the end-effector location. Therefore, the displacement x required to generate the reaction force (normal to surface) is given by

$$x = r - \|d\| \quad (4)$$

The force computed by Eq. 2 is sent to the Arduino board through the serial port, where the torque value required for each motor is calculated as $\tau = J^T F$ by using the following Jacobian matrix of the mechanism:

$$J = \begin{pmatrix} 0 & 0 \\ -l_1\cos(q_1) - l_2\cos(q_1+q_2) & -l_2\cos(q_1+q_2) \\ -l_1\sin(q_1) - l_2\sin(q_1+q_2) & -l_2\sin(q_1+q_2) \end{pmatrix} \quad (5)$$

These torques were mapped to voltage levels. However, the Arduino board is usually not able to provide the power requirements of the actuators,; hence, we used the power electronic system presented in [13].

The electronic system comprises a power amplifier composed of a voltage amplification stage (consisting

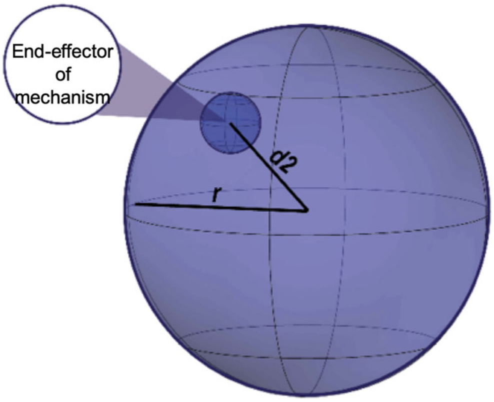

Fig. 2 Hooke's law representation applied to the exoskeleton

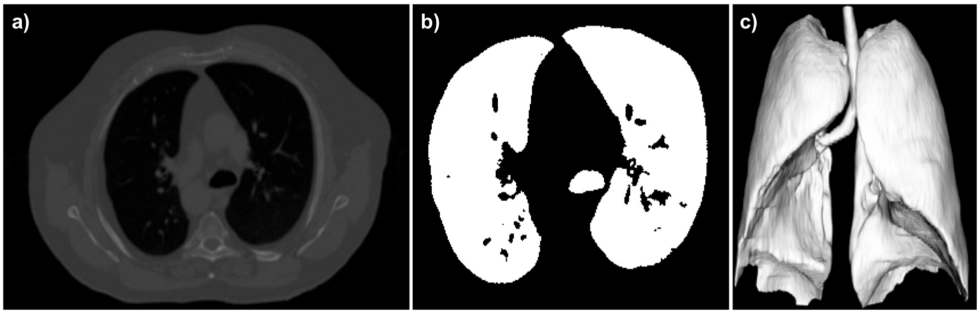

Fig. 3 Results: **a** Original chest CT scan image, **b** Lung segmentation, **c** Three-dimensional lung reconstruction

of two operational amplifiers connected in series with inverting configuration) and a current amplification stage, in which two complementary transistors provide the power required for the actuators. In addition, the PWM output signal of the Arduino board is converted to a differential voltage signal by means of a low pass filter to obtain a voltage that varies from 0 to 5 V (from 0% to 100% of the pulse width). Finally, the output of the power stage is a voltage signal in the range of -6 to 6 V, which is directly connected to the actuator terminals.

3 Results and discussion

3.1 Segmentation and 3D reconstruction of medical images

Figure 3 illustrates the result of segmenting the lung region from the chest CT scan image with the Chan-Vese algorithm [7]. Notice a high degree of definition on the edges of the lungs, even the alveolar ramifications can be observed. Such results suggest that the Chan-Vese algorithm is a suitable method to segment complex structures. In addition, Fig. 3c shows that the the structure reconstructed by the VTK libraries is highly clear and detailed. Finally, Fig. 4 illustrates the two remaining anatomical structures (skull and white matter, respectively). Once more, our results are efficient segmentations and reconstructions, regardless of the type of medical image (CT or MRI).

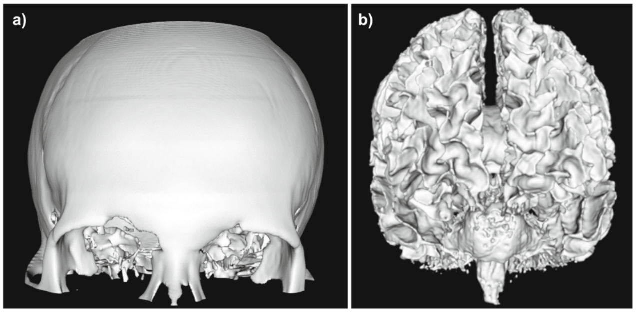

Fig. 4 Results: **a** Three-dimensional skull reconstruction, **b** Three-dimensional white matter reconstruction

3.2 Haptic system (exoskeleton)

Figure 5 depicts the exoskeleton assembled and mounted on the hand, which allows users to interact with the virtual 3D reconstructions. The exoskeleton pieces were 3D-printed using Cubepro's printer.

One of the main advantages of this haptic system with respect to similar commercial products, such as the Phantom omni [14], is that it does not require additional buttons to manipulate virtual objects. Although interaction with virtual objects is achieved through the fingertips and not with the entire surface of the hand - as it would be in real life - our prototype relies on three end-effectors to increase haptic sensation and the system's ability to manipulate virtual objects. Consequently, there is a greater degree of immersion in the system, thereby providing a more realistic experience to users.

Another advantage of our haptic system is that it uses mesh structures. In most haptic devices, it is necessary to use simple figures (e.g. spheres, ellipsoids) to detect collisions and send the corresponding reaction force to the final effector. In our case, the mesh structure allows the system to detect collisions anywhere in the structure of interest, regardless of abrupt changes in the structure's surface shape. This characteristic makes haptic sensations much more realistic.

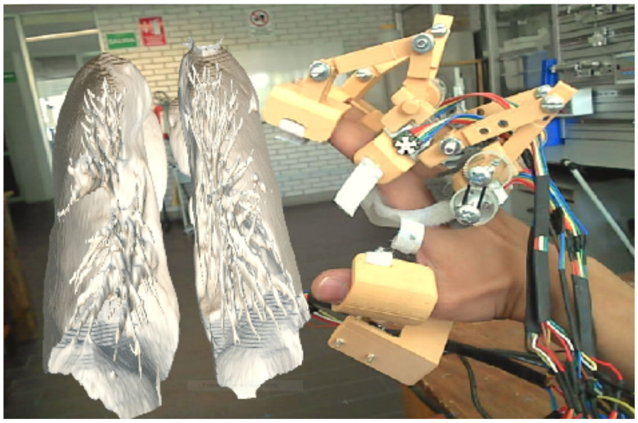

Fig. 5 Physical implementation of the exoskeleton fused with augmented reality

4 Conclusion

This work discusses the development and implementation of an AR interface. The system allows users to manipulate 3D virtual anatomical structures, simply and naturally, having force feedback through a haptic exoskeleton. The results of the segmentation and reconstruction stage indicate that the Chan-Vese algorithm can be remarkably useful in the medical field due to its robustness to segment complex structures. Moreover, VTK helps to obtain high-definition three-dimensional reconstructions that resemble more reality.

The exoskeleton allows users to move the hand naturally and offers a realistic haptic sensation thanks to the three mechanisms that encompass the five fingers. The system can be a useful tool for education and training as a result of its ability to simulate any object or environment using AR. Specifically, our haptic system can be used to train physicians by allowing them to interact visually/tactilely with different anatomical structures and emulate different procedures (e.g. surgeries).

As future work, we will seek to study and simulate the deformation of anatomical structures to increase user immersion in the system. Similarly, we will attempt test the haptic system quantitatively to assess force feedback as experienced by users.

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Compliance with Ethical Standards

Conflict of interests The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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