Hand Motion Capturing and Simulation in Medical Rehabilitation Applications

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Abstract. The paper is dedicated to a problem of hand motion capturing as a part of an intelligent solution for medical and social rehabilitation technology based on the implementation of virtual reality with tactile feedback. Based on related works overview it is proposed to use the system of resistive transducers to develop a mechanical construction for tracking the position of fingers. To capture and formalize the hand motor function a number of kinematic and dynamic parameters are introduced. The sensors provide complete description of the hand motor function in the form of independent coordinates of its movement. Based on this approach there is proposed an original tracking system, which gives a new opportunity to provide a complete description of hand mechanics. From the variety of solutions two prototypes were developed and studied: one with conductive cord and arm, next with flexible PCB prototype with the ability to host sensors. In addition to hand motion capturing solution some recommendations are given to improve its simulation in AR/VR environment. The results of research and development prove the possibility to implement the sensor glove for hand functions rehabilitation in medical applications with the required efficiency.

Keywords: Hand motion capturing · Medical rehabilitation · Intelligent systems application

1 Introduction

Medical rehabilitation is one of the perspective areas of trending information, communication and computing technologies application. Considering the perspective of using new technologies to improve the efficiency of medical treatment and social assistance engineers and doctors combine their efforts to introduce new solutions. One of the challenging problems in this area is lowering of permanent movement disability observed in most cases of stroke consequences. In particular, restoration of the upper limb requires long time and many efforts and in most cases does not fully react against the patient's affect.

Hand functioning rehabilitation is a labour intensive process. This is especially actual for full rehabilitation of fine motor skills, whichcommonly remains impossible

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and leads to severe restrictions in everyday functioning.To provide adequate and sustainable hand motion capture it is required to implement a modern stack of solutions including the Internet of Things, sensors, augmented and virtual reality (AR/VR) and machine learning. Combination of these technologies allows efficient hand motion fixation and simulation in real time.

This task was deeply studied under the project of development of medical and social rehabilitation technology based on the implementation of virtual reality with tactile feedback, carried by Innovations department at Samara State Medical University. Despite the variety of haptic feedback capturing available in the market currently, there was no good tool for cheap and accurate fixation of finger movements. To overcome this difficulty there was developed an original solution presented below.

2 State of the Art

Despite the fact that virtual reality has recently begun to be used for the rehabilitation of patients with neurological disorders, quite a lot of experience has been accumulated in this area. The most intensively virtual reality is currently used to restore postural stability in patients. As you know, the successful maintenance of body stability during standing, walking and any other movements requires the integration of information from the three main sensory systems: visual, proprioceptive and vestibular [1].

In patients with damage to the sensory and associative areas of the brain, the ability to exclude vision and correct postural stability, relying on internal (proprioceptive and vestibular) sensory signals, is usually impaired [2]. This may be due to both general sensory deficits and impaired brain ability to interpret and integrate the received sensory information. As a result, sensory conflict can cause patients to lose their balance and even trigger a fall.

It has been proven that placing a patient in a virtual space with conflicting sensory inputs is an effective way to improve the sensory adaptation necessary to maintain balance. So, in [3] a patient was trained with vestibular disorders so that he could maintain balance while standing on a moving stable platform. The displacement of the platform forward and backward was accompanied by a change in the position of the virtual space in the mediolateral directions. After several repetitions, the patient's ability to maintain a balance disturbed by incoming conflicting information improved.

It was proved that the use of virtual games developed by the VIVID IREX group helps to restore this type of deficiency in patients with post-stroke hemiparesis and damage to the spinal cord and brain [2]. Patients trained to maintain balance during manipulations with virtual objects, for example, beating virtual balls or catching virtual birds. Moreover, patients with gross motor impairment as a result of a spinal cord injury performed the task while sitting in a wheelchair. All participants in the therapy using virtual games significantly improved stability indicators. In addition, they noted increased motivation, interest and a desire to increase the number of procedures, which is important for the rehabilitation of such patients.

Typical hand functions that are impaired in patients with various brain diseases are the ability to reach an object, manipulate it, and coordinate the movements of two hands. The causes of such disorders can be various, but primarily include muscle weakness, changes in the coordination of movements in the joints and the sequence of inclusion of various muscle groups [4].

To prevent the formation of stable motor compensations that interfere with the final restoration of normal movement, M.K. Holden et al. [2] used virtual reality. During the execution of the movement of the hand, the patient was asked to follow the optimal trajectory, which was shown on the screen. Moreover, the patient had the opportunity to synchronize his movements with a moving final trajectory, and with the movement of a virtual hand on the screen. At the end of the course of therapy, significant improvements in the motor functions of the hand were noted in some patients.

Household functions were also trained using games not specifically designed for neurorehabilitation. For example, the computer game Wishy Washy (Sony's EyeToy), which offers participants to wash virtual windows, has improved not only everyday skills, but also the stability of the vertical posture in older people [4].

Therefore there is currently no suitable solution on the market that supports the up-to-datemethodology of restoration of the hand function. It should be capable of fingers motion capturing and simulation in order to support a set of training exercises regularly performed and repeated to guarantee fast and stable results. The most challenging problem is providing adequate feedback from the sensor glove which contains enough number of sensors to track each phalanx.

3 Technologies Overview

The problem of hand movement simulation requires application of various modern technologies including distributed sensors to capture the fingers, computing system to process the movements and generate virtual scenes and AR/VR devices for interactive user interface. Therefore development of modern position tracking systems is concerned with application of Virtual and Augmented Reality [5, 6] used to visualize the simulated objects and provide necessary feedback.

Location and monitoring services to track the position of hand and fingers in real time are usually implemented using built-in sensors and markers, which are placed on the body, gather the required information about its movements and then transmit it to processing unit with the corresponding chains of signals. The basic requirements for such systems require the sensibility and accuracy of the sensors that allow adequate determination of object position in space and time. In case of use of multiple sensors they should be coordinated and function in real time.

One of the possible ways of human body parts monitoring is based on implementation of mechanical tracking technologies [7, 8], which are based on goniometers. This type of sensors allows measuring the rotation angles of the joints to thus determine the final positions of the monitored objects. Under the context of the problem being solved they can be used to determine position of fingertips in space relative to the hand.

The disadvantages of such systems include the difficulty of alignment (a set of operations to align structures and structural elements along a certain direction) of goniometers with joints, especially those with many degrees of freedom. The centers of rotation of the goniometers do not coincide with the centers of rotation of the joints. Due to this kinematic mismatch, slippage or relative displacement takes place between the goniometer mount and the limb during displacement. Human joints are not ideal: the axis of rotation moves when the angle of rotation of the joints changes. To increase accuracy, appropriate calibrations must be used.

The algorithm of the mechanical tracking systems includes the following:

- the mechanical sensors mounted on the arm provide data on the degree of bending of each joint;
- data is interpreted as a rotation angle;
- data is transferred to the kinematic model of the hand;
- sets of sensors are used that track the movement of the finger mechanically – for example, load cells, servo sensors, etc.;
- a set of sensors is placed on the glove, in some cases in an additional rigid exoskeleton of the hand;
- sensor data are interpreted as rotation angles of the joints and transferred to the kinematic model of the arm.

Mechanical tracing provides comparatively high accuracy and is simpler in construction and production, which can be which can be attributed to the undoubted advantages. The limitations include lower reliability and possible user experience discomfort caused by the necessity to wear on the body sensors and wires. The most illustrative example of such kind of a system is an exoskeleton.

The quality of a mechanical tracking system can be sufficiently improved by using the resistive transducers, which allow improving the basic algorithm the following way:

- sensors on the phalanx give values that are interpreted as stretching;
- stretching according to calibration is translated into the bend angle of a particular phalanx;
- bend angles are mapped onto a kinematic model;
- resistive load cells - resistance changes depending on stretching;
- a set of sensors is placed on the glove.

The advantages of mechanical systems with resistive sensors include higher accuracy, simpler calibration and stability of the data collecting and transmitting processes, relative compactness and lightness of the hardware. The main disadvantage of mechanical systems with resistive sensors is concerned with possible discomfort when using the specifically designed gloves.

4 Hand Tracking and Visualization Features

Hand simulation in medical rehabilitation applications requires tracking of spatial position of fingers and visualization of their movements in 3D scene using VR goggles. Simulation results should look realistic for the user; therefore 3D model of the hand should be built using high-precision three-dimensional mappings in real time. The basic requirement for tracking is the high intuitiveness and naturalness of the interaction, close to that of real-world objects.

To solve medical rehabilitation problems the hand model should consider and reproduce the functional state of the hand. Using one sensor per finger is not enough since it is not able to track typical movements of fingers conducting simple hand actions. Consequently it was proposed to place a separate sensor on each phalanx and coordinate them as the parts of a solid model.

To identify each movement with satisfactory quality there can be introduced a number of indicators. For example, the relative distance of the finger tips comparative to the palm allows understanding possible options of hand positions; and further analysis of its changes makes it possible to improve the level of accuracy and determine the right position and movement.

For rehabilitation purpose it is important to identify the positions of fingers at their maximum flexion, the distance between the tips of the thumb and forefinger when they are closed, and the resulting grip force. The patient usually carries out a number of exercises trying to perform necessary movements to join the fingers in various orders. In clinical practice understanding of fingers relative positioning is used to study various pathological conditions.

Biomechanical parameters for research include:

- angles of abduction of the thumb and little finger;
- range of motion in the wrist and metacarpal joint of the thumb;
- range of motion in the metacarpophalangeal joints;
- bending angles of all fingers;
- the angle of flexion of the wrist joint.

Based on the analysis of these parameters there can be gathered a complete description of hand functioning necessary for diagnostics and rehabilitation procedure organization. Their evaluation requires determination of interdependent coordinates of finger phalanx. The proposed solution requests positioning the sensors located on each phalanx of each finger of the hand as shown in Fig. 1.

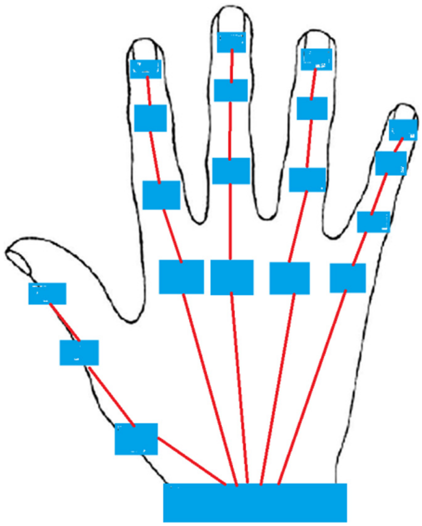

Fig. 1. The location of the sensors on the hand

The sensors should be incorporated into a solid system, capable to associate the measured positions of phalanx and balance the evaluations on order to reduce the error accumulation. The resulting kinematic model is build considering the estimated positions using mathematical laws, which allows providing adequate accuracy and targeting the high immersive effect.

In addition to this, analysis of the tracking history and context of rehabilitation procedure (like e.g. types of required actions that patient performs at certain time) helps improving the quality and accuracy of simulation.

The context of the user's activity can be analyzed at processing stage by and adaptation algorithm and used later to coordinate and correct the results of fingers' movements tracking. This approach allows considering the features of patients' perception as well. Some ideas of the user activity analysis are presented in [9, 10].

Current functional state and movement of the hand is visualized for the patient using virtual reality. Hand visualization itself is a complex task as soon as it requires animation of many fingers positions. Therefore when simulation the process of "grab" some object with the hand in most simulating solutions the hand is not represented itself, but often replaced by the object. Still some visualization of the fingers and their current position provides a greater presence effect and is more preferable for realistic immersion.

This is true in the case of using the Oculus Touch due to ergonomics. However in some projects using Vive with their current version of the controller, the effect sometimes appears that the user does not hold the object with a virtual hand, but the virtual hand itself is holding the object. This probably depends on the specific use cases and the specific angles of rotation of the object and hand.

Moreover, in the option with showing only the object in the hand, there is no sensation of the avatar disappearing or simply losing contact with it (after the disappearance of virtual hands), since at this moment the whole focus is transferred to the object itself.

Possible solutions include developing a "wax" model or representing the hand by a hand of a robot or a special glove. The "empty glove" effect is based on the effect of transparency. The glove takes the shape of the hand and justifies it visually, which solves the problem of the ephemerality of the virtual hand. At the same time it does not require complex visualization and animation with photorealistic effect.

When using VR goggles the real hand position should be synchronized with the simulated virtual hand. However movement of a virtual hand cannot be terminated by other virtual objects in 3D scene. If the hand crosses any geometry in scene it with go through it. Still in case the hand is visually translucent it does not cause any logical dissonance. In addition to this the events of intersection of the virtual hand with other objects in scene can be signalized by means of vibration.

Visualization of the shadow from the hands also helps in determining the position of the hands in space, and also creates a connection between the hands and the virtual environment. Since the user associates virtual hands with him this strengthens his connection with the virtual environment.

The described above implementation features provide the effect of realistic and immersive simulation suitable for hand rehabilitation applications.

5 Implementation Results

Solving the task of computer modeling, hands are represented as a mechanism from a system of bodies connected with each other with certain degrees of freedom of movement. The bones are simulated by separate bodies rotated relatively to each other in a corresponding association considering the spatial orientation of the entire arm. Therefore sensors should capture these positions with lowest possible deviations.

The developed prototypes are presented in Fig. 2.

Fig. 2. Prototype with conductive cord and arm (at the left). and flexible PCB prototype with the ability to host IMU sensors (at the right)

To obtain data from the glove, a binary serial data protocol is used. Data is transmitted through a virtual serial port, implemented through the Bluetooth protocol stack.

The main algorithm of data transfer includes the following steps:

1. Activation of the Bluetooth protocol on a personal computer and gloves;
2. Pairing the Bluetooth stack of the personal computer and the Bluetooth glove stack while maintaining the identification of the glove instances (right, left);
3. Coordination of a virtual serial data channel;
4. Initialization of the working status of the serial data channel;
5. Obtaining configuration data for each glove;
6. Obtaining the functional status of electronic equipment gloves;
7. Initialization of the data transfer mode of the glove sensors data stream;
8. Receiving a glove sensors data stream.

Information exchange can be carried out only between the master and slave devices. Each device can be either a master or a slave, and the connection of devices between themselves forms a network called a piconet (personal network) with the following characteristics:

- in one piconet there is only one master device, all the rest are subordinates;
- the maximum number of devices of one piconet simultaneously participating in the transmission of information is not more than 8;
- the total number of devices connected to the master device is not limited;
- at each moment, data can only be exchanged between two devices in one direction.

Set of piconets is formed by overlapping individual piconets, where each device of one piconet can enter another piconet both as a subordinate and as a master.

Basic Bluetooth network states are implemented:

- idle – low power consumption, only the device's clock works;
- connection status – the device is connected to the piconet;
- parking status – the status of a slave device from which it is not required to participate in the piconet, but which should remain part of it.

Intermediate states for connecting new slaves to the piconet include:

- polling – determination by the device of the presence of others within its reach;
- polling search – waiting for a polling device;
- response to the survey – the device that received the survey responds to it;
- request – sent by one device to another to establish a connection;
- request search – the device is waiting for a request;
- response of the slave – the slave responds to the request of the master;
- response of the master – the master device responds to the subordinate after receiving from him a response to the request, neuroplasticity and virtual reality.

The essence of the mathematical model of the hand in the VR environment is to simulate the folding of the phalanges of the fingers by manipulating certain coefficients that characterize the angles between the phalanges (see Fig. 3).

The results of hand motion capturing and simulation are illustrated by Fig. 4.

The proposed solution allows achieving accuracy and adequacy of movements sufficient to satisfy the requirements of medical rehabilitation applications. From some device designed to read the movement of the hand, data is taken, which are converted into corners for the corresponding limbs. These angles are applied to the hand model, after which the simulated arm begins to move in the VR environment identically to the real arm with which the data is taken.

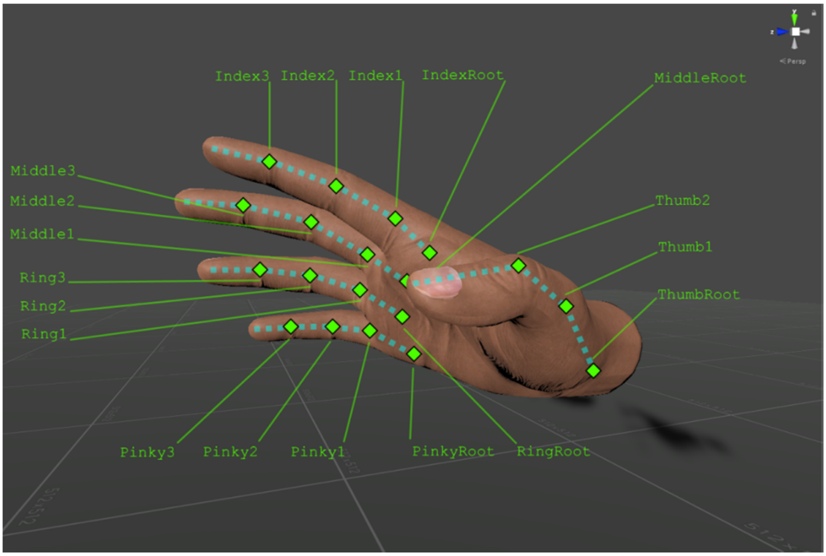

Fig. 3. Handmathematical model in VR

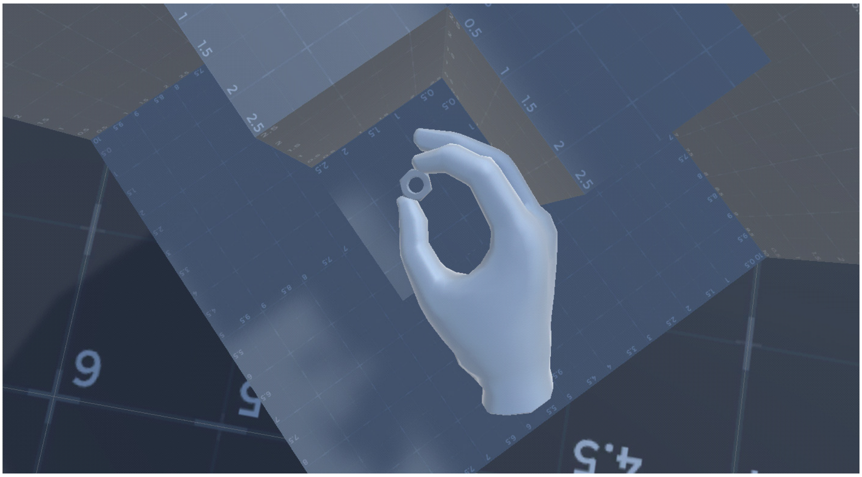

Fig. 4. Hand motion capturing and simulation result

6 Conclusion

Virtual reality solutions with haptic feedback are highly required in medical and social rehabilitation innovations. The sensor gloves that implement mechanical tracking of finger phalanx positions using the resistive transducers provide an increased quality of hand motion fixation. The most perspective constructions include the one with conductive cord and arm, and the second with flexible PCB prototype with the ability to host sensors. The proposed solution allows achieving the required accuracy and adequacy.

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