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Overall design and implementation of the virtual glove

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ABSTRACT

Post-stroke patients and people suffering from hand diseases often need rehabilitation therapy. The recovery of original skills, when possible, is closely related to the frequency, quality, and duration of rehabilitative therapy. Rehabilitation gloves are tools used both to facilitate rehabilitation and to control improvements by an evaluation system. Mechanical gloves have high cost, are often cumbersome, are not re-usable and, hence, not usable with the healthy hand to collect patient-specific hand mobility information to which rehabilitation should tend. The approach we propose is the virtual glove, a system that, unlike tools based on mechanical haptic interfaces, uses a set of video cameras surrounding the patient hand to collect a set of synchronized videos used to track hand movements. The hand tracking is associated with a numerical hand model that is used to calculate physical, geometrical and mechanical parameters, and to implement some boundary constraints such as joint dimensions, shape, joint angles, and so on. Besides being accurate, the proposed system is aimed to be low cost, not bulky (touch-less), easy to use, and re-usable.

Previous works described the virtual glove general concepts, the hand model, and its characterization including system calibration strategy. The present paper provides the virtual glove overall design, both in real-time and in off-line modalities. In particular, the real-time modality is described and implemented and a marker-based hand tracking algorithm, including a marker positioning, coloring, labeling, detection and classification strategy, is presented for the off-line modality. Moreover, model based hand tracking experimental measurements are reported, discussed and compared with the corresponding poses of the real hand. An error estimation strategy is also presented and used for the collected measurements. System limitations and future work for system improvement are also discussed.

1. Introduction

Patients suffering from residual hand impairments, following a stroke or after surgery, need rehabilitation therapy. Each exercise has several levels of difficulty corresponding to the maximum force that can be applied, duration, and other parameters. During exercise, often an elastic object is squeezed by the patient to recover strength. It has been demonstrated that training results have to be continuously controlled by a therapist to be effective [1].

Traditional rehabilitation is done one-to-one, namely, one therapist (or sometimes several) working with one patient. Costs are high, especially for demanding patients, and monitoring is leaved to the experience of the therapist, without objective measurements. Regarding the therapy that the patient does at home, there is currently no monitoring. Recent studies suggested that repetitive and long duration training using auxiliary systems and virtual reality or augmented reality is helpful [2–5]. This context highlights the importance of having an assisting, possibly automatic, rehabilitation system whose data are numerically analyzed and transmitted, through internet, to the healthcare structures. The numerical evaluation and comparison over the time could represent a reference strategy to evaluate the rehabilitation progresses, in an objective way, with a precision which is of the order of some millimetres at a high temporal resolution, instead of a subjectively evaluated monitoring without comparison with previous data. Moreover, it could provide a useful tool to monitor rehabilitation performed at home.

Several of these integrated systems, exploiting haptic glove based interfaces, have been designed for virtual reality simulation, such as: the Rutgers Master II-ND glove [6], the CyberGrasp glove [7], the LRP glove [8], integrated versions of them [9], or other pneumatic gloves [10,11]. In these systems, the mechanical unit interacts both with the hand of the patient and with a virtual reality environment during rehabilitation. Despite the undoubted advantages in the use of such rehabilitation systems, haptic gloves have several force feedback terminals per finger with the forces

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grounded in the palm or on the back of the hand which make them heavy (some hundreds of grams), cumbersome and greatly limiting of natural and spontaneous movements. Moreover, they can be very expensive due to their personalized electronic and mechanical components. In addition, each device has to be constructed specifically for each patient, taking into consideration the patient's residual infirmities. This seriously limits re-using both the mechanical device and the associated control system. Moreover, the patient can tend to rely too much on the device rather than using his own hand when becomes familiar with the assisting device. An alternative approach is to use virtual glove based interfaces to replace the electro-mechanical gloves [12–17].

The approach we propose, completion of [12–14], is based on this latter kind of interface. The system aims to assist and monitor hand movements with acceptable spatial precision and good temporal resolution to allow an objective evaluation of the rehabilitation progresses. The proposed system should overcome most of the limitations of mechanical gloves, in particular: high cost (the cost of a mechanical glove is about 20,000–30,000 USD); use difficulty (a mechanical glove has to be correctly worn and properly set); no re-usability (a mechanical glove is often personalized and cannot be used by different patients); impossibility to set the optimal recovery level (a mechanical glove cannot be used for the healthy hand in order to evaluate the personalized optimal recovery level to whom the rehabilitation should tend).

The proposed system consists of a cubic box in which the hand of the patient is inserted. The hand movements are collected by a set of video cameras positioned on the vertexes of the cube and tracking is performed. Tracking is used to determine position, orientation and articulation of the hand over the time. However, building a fast, efficient and effective stereo vision based tracker for the hand is still a challenging issue. This is due to several factors, such as: ambiguities due to occlusions, high dimensionality of the problem, noise in the measurements, lack of visible surface texture, significant lighting variations due to shading. Monocular vision approaches are even more difficult due to depth ambiguities [18–21]. Approaches based on the analysis of data collected by depth sensing video cameras (3D cameras) [22] have greater occlusion issues than stereo vision approaches if a single 3D camera is used. A huge number of papers dealing with hand and fingers tracking has been published [23–32]. A possible classification can be done according to the use, or not, of markers to support tracking:

- *marker based hand tracking approaches* [27–29]: Use passive (i.e. colored or reflective materials) or active (i.e. LEDs providing fixed or modulated lights) markers placed on specific landmarks. The coordinates of these points are used to update the hand model state;
- *markerless hand tracking approaches* [30,31]: Based on the back projection technique [32]; the 3D visual hall of the hand is obtained from inverse projection of different silhouette views of the hand.

Detailed description of the presented classification can be found in [33,34]. The method we describe uses a set of colored passive markers placed on fingertips and on the back of the palm.

The hand tracking is associated to a numerical hand model [13,14] that is used to calculate some useful parameters without using electro-mechanical haptic interfaces. This design allows a very accurate calculation of physical, geometrical and mechanical parameters, including hand, fingers and joint positions, movements, speed, acceleration, produced energy, motion direction, displacements, angles, applied forces, and so on.

While in previous works we described the virtual glove general concepts [12], the hand SimMechanics model [13] and its characterization including the system calibration strategy [14] in an off-line modality, the present paper provides the final virtual glove ensemble applied to hand, fingers and finger joints tracking, both in real-time and in off-line modalities. The first, the real-time modality, is used to drive the exercises and has to be fast enough to offer the patient a real-time interaction with the virtual environment and a general, qualitative, evaluation of how the exercise is doing. The second, the off-line modality, is used to measure hand movements and to calculate physical and mechanical parameters to offer to the therapist an objective analytical, quantitative, evaluation of the results. Quantitative calculations can be executed after the rehabilitation session is terminated.

In what follows, the real-time modality is described and implemented and a marker-based hand tracking algorithm, including a marker positioning, coloring, labeling, detection and classification strategy, is presented for the off-line modality. Moreover, preliminary model based hand tracking experimental measurements are reported, discussed and compared with the corresponding poses of the real hand from different views through the reprojection error.

A marker-based approach is used because our aim is to recognize the joints of the hand with accurate, and reproducible, spatial accuracy. Moreover, a marker-based approach can be useful to reduce the number of occlusions by installing rigid protruding markers either directly on the fingertips or inserted into an object to be grasped by the patient (for example a pegboard).

The paper is structured as follows. Section 2 reviews the high level description of the virtual glove, illustrating its usage both in real-time and in off-line modality, with particular attention to the accurate hand model used for the off-line modality, providing details for the numerical model constraints and approximations. Section 3 presents the hand tracking strategy used to extract useful information from the recorded video streams coming from the synchronized cameras. Details regarding markers disposition and coloring, detection approach, and classification process are also provided. Section 4 reports and discusses experimental hand tracking measurements and error analysis. Section 5 concludes the paper and provides some issues on which we are currently working to improve the system.

2. The virtual glove design

Fig. 1 presents the high level architecture of the virtual glove system. It has the following structure:

a. The *Glove Box Module* consists of a cube-shaped glass box, side dimension of 60 cm, and a support positioned in the upper face. At the center of two lateral faces of the cube, opposite one another, circular holes are produced to insert the hand inside the cube. Holes in opposite faces serve to analyze either the left hand or the right hand (data collected from the healthy hand can be very useful, for reference), if camera asymmetrical configurations are used: most of the useful information is located on the back of the hand (see below). The support in the upper face of the box hosts a 3D depth sensing camera. The camera distance from the center of the box is 100 cm. The depth sensing camera has to provide a video stream to feed a virtual reality module, implementing the real time modality. The box is used both to sustain the hand and for housing, on some of its vertices, four 2D video cameras. The video cameras supply four synchronized video streams that provide the information to reconstruct, track and analyze hand movements in the off-line modality. The video streams are collected, stored in memory, and processed at a later time. Each video camera is at about 53 cm from the center of the box. In this way, a useful