Animating a synergy-based deformable hand avatar for haptic grasping

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Abstract. A 3D deformable hand avatar for virtual grasping using multiple single-contact-point haptic devices is introduced. The proposed technique has two main advantages. First, the whole hand motion is reconstructed by measuring only fingertips positions and using a biomechanical model of the hand along with the postural synergies characterizing grasping actions. Secondly, this technique requires only simple algebraic computations.
Keywords: hand, grasping, multicontact, synergies, animation.

1 Introduction

Haptically enabled applications are getting widespread also for end users that are not very familiar with virtual reality. In spite of the great deal of development, often users complain they cannot see an avatar of their hands in the virtual simulation scenario, thus losing a relevant visual feedback commonly available in reality. To provide for this lack, two main approaches can be found in the literature: the first consists in representing a low-detail avatars using sets of geometrical primitives (cylinders and spheres), whose computational complexity allows real-time simulations [1]. The second is based on precomputing several deformation patterns for a 3D hand model and interpolating them to perform data-driven real-time animation [2]. Anyway, both approaches are characterized by the use of multifingered devices or gloves featuring high number of sensors to capture the real hand motion.

Our approach consists of realizing a high-realism hand avatar that can be animated in virtual grasping applications using some single-contact-point haptic devices. Such devices allow to capture only fingertips motion, therefore the movement of the whole hand is reconstructed using a biomechanics-based kinematical model and exploiting a neuroscience-based technique to reduce the number of degrees of freedom (DoFs). In particular, recent studies in [3, 4] demonstrated that, notwithstanding the complexity of the human hand, a few input control variables, named *postural synergies*, are able to account for most of the variance in the patterns of hand movements and configurations in manipulation and grasping tasks. These conclusions were based on the results of experimental tests in which subjects were asked to perform grasping actions on a wide variety of objects. Data were recorded by means of data gloves and were analyzed with the Principal Component Analysis (PCA) technique. Our assumption is that the *postural synergies* can be represented as a joint displacement aggregation corresponding to a reduced dimension representation of hand movements. In other words, the synergies are a set of dependencies among the hand joints angles that allow to accurately approximate the hand shape in grasping tasks reducing the number of DoFs. Their main advantage is that just few synergies are sufficient to reasonably approximate the general shape of the hand during a grasp, while higher-order synergies account for finer and subtle adjustments of fingers depending on the target object shape.

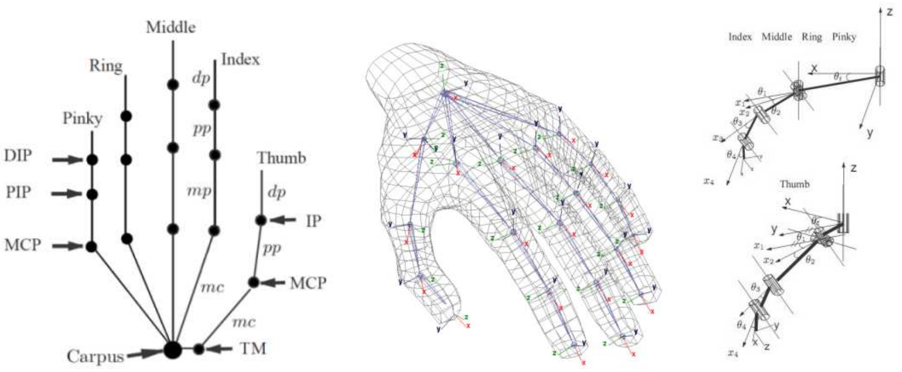
Hence, the key idea of the proposed technique consists in capturing only the motion of some fingertips, e.g. index and thumb, transforming measures in the related joint-space trajectories and using synergies to suitably distribute such trajectories to the whole hand joints. Once the current kinematic configuration of the hand skeleton has been computed, the consequent skin deformation is achieved using a smooth skinning technique. This solution involves only algebraic computation for kinematic inversion, and requires no time-consuming optimization neither the online solution of dynamic equations.

This work presents an application of the proposed technique in a virtual pinch grasping simulation, involving the index and the thumb fingers. The remainder of this paper is structured as follows: in Section 2 the design of the 3D model is discussed; Section 3 reports the animation controller; Section 4 presents the implementation; finally, in Section 5 the concluding remarks are drawn and the future research perspectives are discussed.

2 Modeling the deformable hand avatar

The deformable hand avatar has been realized using a 3D skinned mesh. A hierarchical skeleton has been bound to a static hand mesh, according to hand biomechanical models available in the literature [5–7]. Referring to the Figure 1.a, each finger has the metacarpal (mc) bone fixed with respect to the hand frame, and features four degrees of freedom (DoFs), hence the mesh skeleton globally features 20 DoFs. The TM joint of the thumb as well as the MCP joint of the index, middle, ring and pinky fingers have two DoFs each (one for adduction/abduction and another flexion/extension). The MCP and IP joints of the thumb, as well as the PIP and DIP joints of the other fingers have one DoF each (joint names acronyms: metacarpophalangeal(MCP), proximal interphalangeal (PIP), distal interphalangeal (DIP), trapeziometacarpal (TM), interphalangeal (IP); bone names acronyms: metacarpal (mc), proximal phalanx (pp), middle phalanx (mp), and distal phalanx (dp)).

As shown in Figure 1.b, we assume that the hand reference frame is attached to the carpus. Each finger is modeled as a kinematic chain whose joints are displaced accordingly to the main degrees of freedom of a real hand. The kinematics



(a) (b) (c)

Fig. 1. (a) Bone-joint structure of the hand skeleton. (b) 3D avatar. (c) The DH representation for the index and the thumb fingers.

of each finger have been modeled using the Denavit-Hartenberg (DH) representation [8] (see Figure 1.c), hence the hand configuration can be represented by the joint variables vector $\mathbf{q}$ defined as:

$$\mathbf{q} = [\mathbf{q}_T^T \;\; \mathbf{q}_I^T \;\; \mathbf{q}_M^T \;\; \mathbf{q}_R^T \;\; \mathbf{q}_P^T]^T \quad \in \mathbf{R}^{20\times 1} \tag{1}$$

The bone lengths have been chosen according to the anatomy of the real hand skeleton. In absence of disabilities or handicaps, the ratios between the bones lengths of each finger are almost constant [9]. Hence, in Table 1 we report the bone length ratios defined with respect to the length of the distal phalange of each finger [10]. Besides, we report also the DH parameters of the fingers, for the sake of simplicity only for the index and the thumb [7].

Finger		mp/dp	pp/dp	mc/dp
Thumb	right	–	1.37	2.09
	left	–	1.36	2.08
Index	right	1.41	2.45	4.17
	left	1.41	2.44	4.10
Middle	right	1.60	2.54	3.71
	left	1.59	2.54	3.71
Ring	right	1.50	2.33	3.25
	left	1.49	2.31	3.22
Pinky	right	1.15	2.04	3.32
	left	1.16	2.04	3.32

Thumb			
a_i	α_i	d_i	q_i
a_o	0	d_1	-51^o
0	90^o	0	q_0
mc_T	90^o	0	q_1
pp_T	0	0	q_2
dp_T	0	0	q_3

$[q_0 \; q_1 \; q_2 \; q_3]^T = \mathbf{q}_T^T$

Index			
a_i	α_i	d_i	q_i
mc_I	0	0	-22^o
0	-90^o	0	q_4
pp_I	0	0	q_5
mp_I	0	0	q_6
dp_I	0	0	q_7

$[q_4 \; q_5 \; q_6 \; q_7]^T = \mathbf{q}_I^T$

Table 1. Table of bone-to-bone length ratios, and Denavit-Hartemberg parameters for the thumb and the index.

To easily achieve deformable avatar skin, a set of influencing skeleton joints is assigned to each vertex of the mesh, along with a weight factor per influence (*blending weights*). With this strategy, the current position $\mathbf{v}_i^c$ of the i^{th} vertex can be achieved as a linear combination of the bone rigid transformations, taking the weights into account:

$$\mathbf{v}_i^c = \sum_{j=1}^{m} w_{ij} \mathbf{H}_j(\mathbf{q}) \mathbf{v}_i^0 \qquad (\sum_{j=1}^{m} w_{ij} = 1, \quad i = 1, ..., n) \tag{2}$$

where w_{ij} is the weight of the j^{th} joint assigned to the i^{th} vertex; $\mathbf{H}_j(\mathbf{q})$ is the current global transformation of the j^{th} bone; $\mathbf{v}_i^0$ is the i^{th} vertex rest pose; m is the number of influencing bones; n is the number of mesh vertices [11].

3 Animation Control

A large number of degrees of freedom characterizes the problem of animating the hand avatar. The biomechanical model we use to define the mesh skeleton globally features 20 degrees of freedom (DoFs). In this preliminary study, we decided to not to include the wrist motion in the synergy-based animation control, leaving it to future developments. The test application consists of a pinch grasping task, involving only two haptically-enabled contact points for the thumb and for the index, respectively. This yields 6 measured DoFs. The measured DoFs are less than those of the hand skeleton, hence the animation controller is expected to solve the kinematical redundancy relying on the hand model, using the postural synergies to propagate the motion also to the other fingers that are not directly captured by the haptic devices.

The postural synergies represent a set of linear dependencies between the joint variables of the whole hand, therefore they allow to univocally define the hand posture through a number of degrees of freedom lower than 20. In this work, the mathematical definition of synergies is a simplification of the one proposed in [12] for the control of robotic hands, hence:

$$\mathbf{q} = \mathbf{S}\boldsymbol{z} \tag{3}$$

where $\boldsymbol{z} \in \mathbf{R}^{n_z}$ is the vector of synergy variables, n_z is the number of the involved synergies, $\mathbf{S} \in \mathbf{R}^{20 \times n_z}$ is the synergy matrix, whose columns describe the shape of each linear dependency.

In the application of interest, the key idea consists of evaluating the postural synergy variables using an inverse kinematics algorithm based on transpose jacobian matrices [13]. Since only real thumb and index are captured by the haptic devices, only the jacobian matrices of these fingers are taken into account along with the related $m = 8$ joint variables $\overline{\mathbf{q}}^T = [\mathbf{q}_T^T \ \ \mathbf{q}_I^T]$, yielding:

$$\mathbf{J}(\overline{\mathbf{q}}) = diag\{\mathbf{J}_T(\mathbf{q}_T), \mathbf{J}_I(\mathbf{q}_I)\} \quad \in \mathbf{R}^{6 \times m} \tag{4}$$

Now let $\mathbf{x}_I(t)$ and $\mathbf{x}_T(t)$ be the real fingertip positions of operator's index and thumb, respectively. Similarly, let $\hat{\mathbf{x}}_I(t)$ and $\hat{\mathbf{x}}_T(t)$ be the fingertip positions of the avatar index and thumb, respectively. The avatar tips are coupled to the corresponding operator's tips through a virtual spring, hence at each time instant t, $\mathbf{F}_I(t) = k_{vc}(\mathbf{x}_I(t) - \hat{\mathbf{x}}_I(t))$ and $\mathbf{F}_T(t) = k_{vc}(\mathbf{x}_T(t) - \hat{\mathbf{x}}_T(t))$ are the force required for the avatar fingertips to track the real fingertip trajectories measured by the haptic devices.

The forces $\mathbf{F}(t) = [\mathbf{F}_T^T(t),\ \mathbf{F}_I^T(t)]^T \in \mathbf{R}^{6\times 1}$ reflect on the synergy-space generalized forces $\boldsymbol{\sigma}(t)$, defined as:

$$\boldsymbol{\sigma}(t) = \overline{\mathbf{S}}^T \mathbf{J}^T(\mathbf{q})\mathbf{F}(t)$$

where $\overline{\mathbf{S}} \in \mathbf{R}^{m\times n_z}$ has the first m rows of $\mathbf{S}$, i.e. those related to thumb and index. Now the new kinematic configuration in the synergy-space can be updated as:

$$\boldsymbol{z}(t+1) = \boldsymbol{z}(t) + k_\sigma\ \boldsymbol{\sigma}(t)$$

where k_σ is a constant factor determining the responsiveness of the animation. Finally, the joint-space configuration $\mathbf{q}(t+1)$ required to give the 3D avatar the desired shape at time $t+1$ is computed according to the (3):

$$\mathbf{q}(t+1) = \mathbf{S}\boldsymbol{z}(t+1)$$

In order to avoid unnatural finger positions, the equation above has been combined with the following set of angle constraints [14]:

Finger	q_1	q_2	q_3	q_4
Thumb	$-10^o,\ 80^o$	$0^o,\ -55^o$	$0^o,\ -55^o$	$0^o,\ -40^o$
Index	$0^o,\ 90^o$	$-15^o,\ 15^o$	$0^o,\ 110^o$	$0^o,\ 90^o$
Middle	$0^o,\ 90^o$	$-12^o,\ 12^o$	$0^o,\ 110^o$	$0^o,\ 90^o$
Ring	$0^o,\ 90^o$	$-10^o,\ 10^o$	$0^o,\ 110^o$	$0^o,\ 90^o$
Pinky	$0^o,\ 90^o$	$-12^o,\ 12^o$	$0^o,\ 110^o$	$0^o,\ 90^o$

Table 2. Allowed ranges for the joint angle variables.

Once the current kinematic configuration $\mathbf{q}$ of the skeleton has been determined, the skin deformation is finally achieved by computing the resultant transformation of all the mesh vertices using the equation (2).

In summary, the proposed animation controller is able to approximate the principal motion components of all the avatar fingers taking only the real index and thumb fingertip trajectories as inputs. Note that the equations discussed so far involve only simple algebraic computations.

4 Implementation

A demonstrative application has been developed to evaluate the avatar animation controller in a virtual pinch grasp involving the thumb and the index. The attention was mainly addressed to evaluate the realism of animation for the other fingers, determined by the use of postural synergies.

As already mentioned in the previous section, the proposed technique still cannot account for the wrist motion. In this demo application, wrist rotation is neglected as well, but a simple strategy has been studied for wrist translation according to the measured fingertip trajectories. Let $\mathbf{P}_w$ be the position of the wrist reference frame with respect to the base frame. At each time instant, the average force $\mathbf{F}_w$ between the virtual coupling forces at index and thumb fingers is computed. Then, $\mathbf{F}_w$ is used to assign a desired velocity $\dot{\mathbf{P}}_w$. The discrete-time wrist update rule can be written as:

$$\mathbf{P}_w(t+1) = \mathbf{P}_w(t) + k_w \mathbf{F}_w \tag{5}$$

The hand skinned mesh as well as the skeleton design have been realized using Autodesk Maya 2008. The demo application has been coded in C++ on Win32 API for WindowsXP, using DirectX and HLSL shaders for graphic rendering on the GPU. Haptik Library for the low-level access to haptic devices [15], Libralis Library [16] for gravity compensation, nVidia PhysX SDK for the physics engine on GPU. The haptic rendering has been performed via a classic visco-elastic contact model to feed forces back, using the Friction Cone [17] and Soft-Finger [18] algorithms to simulate contact friction. Clearly, the haptic feedback can be rendered only to the index and the thumb, currently the other fingers are only animated to improve the simulation realism. The following parameters were used to set up the hand model and the animation controller: $k_{vc} = 0.05$, $k_\sigma = 0.004$, $dp_I = 19$mm, $dp_T = 22$mm. In Figure 2 we reported a picture of the experimental setup, consisting of two Omega Haptic Devices featuring a finger-thimble end-effector. The Figure 3 shows some screenshots taken from the running application, where virtual objects (a sphere or a cube) are grasped by a left-handed operator.

Fig. 2. The experimental setup.

5 Conclusion and Future Works

The work discussed in this paper consists of developing a deformable hand avatar and its animation control to be employed in virtual reality using commercial single-contact-point haptic devices such as the Omega or the PHANToM. A

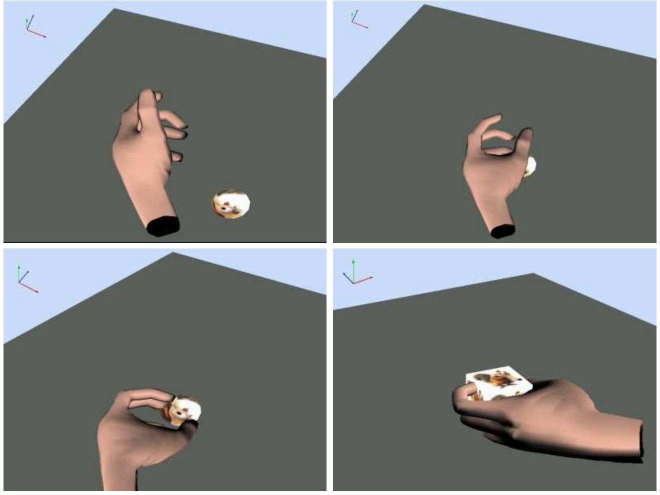


Fig. 3. Some screenshots from the pinch-grasping demo application.

kinematic skeleton featuring 20 DoFs has been designed according to the biomechanics of the hand. Besides we took advantage from the postural synergies, i.e. a set of dependencies among the hand joints angles that allow to accurately approximate the hand shape in grasping tasks reducing the number of DoFs. Therefore, the proposed animation technique consists in capturing the motion of some fingertips, transforming measures in the related joint-space trajectories according to the biomechanics-based kinematical model, and finally using postural synergies to distribute the angular displacements to the whole hand joints. Once the current kinematic configuration of the hand skeleton is available, the consequent skin deformation is computed using a smooth skinning technique. This algorithm involves only algebraic computation for kinematic inversion, and requires no time-consuming optimization neither the online solution of dynamic equations. This solution has been applied in a demo application to simulate pinch grasping with the index and the thumb. Given the low computational load of this technique, it does not affect the realism of haptic rendering.

In our future perspectives, we plan to carry out several experiments to numerically evaluate the motion approximation performance with respect to the number of employed synergies. Besides we aim at improving the animation controller including also the wrist motion.

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