Simulating Deformable Contact Property of Digital Hand Skin

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The virtual ergonomic assessment based on Digital Hand which estimates grasp posture and evaluates the quality of grasp is valuable for hand-held product design. In this paper, we propose the method to implement deformable property caused by a contact between Digital Hand and the product surface by modeling the fingers as "quasi-rigid" objects, by constructing a physical model based on Boussinesq formula which approximates skin contact deformation mechanism, by detecting collision between Digital Hand and a product surface and enlarging the collision area, and then by finally solving Linear Complementarity Problem to resolve the contact and to produce the visible skin surface deformation. The plausible skin deformation could be obtained, because the method preserved the volume of Digital Hand before and after the skin deformation. In addition, utilizing the locality property of the deformation, the method can be easily used by the existing Digital Hand model.

1.Introduction

Currently, virtual ergonomic assessments based on Digital Hand play an important role for hand-held product manufacturers to gain their market competitiveness, because it can save the cost of test subjects, time, fabricating physical mockups, and it also enables objective evaluation. Much work has been reported recently in this field [1 - 4](see Fig.1). But the models of their human hand did not simulate skin deformation caused by a contact, and, instead, approximated it in a simple way in which collisions between Digital Hand and product surface below a specific threshold were allowed as shown in Fig.2. If the contact area and the contact forces are just approximated roughly, this will result in the loss of accuracy of grasp posture stability.

Simulating the soft tissue deformation of human hand which has non-linearly elasticity, based on FEM, could realize relatively high accuracy. However, FEM requires a great deal of execution time, which is unacceptable for a digital hand system. Therefore, this paper proposes a relatively fast method of simulating the skin deformation caused by a contact by modeling human hand as a "quasi-rigid" object[5], by introducing and modifying Boussinesq approximation to realize the volume preserving property of hand tissue, and finally by solving the LCP to implement surface skin deformation caused by a contact.

2. Skin Deformation caused by a Contact

The proposed skin deformation method, in which Digital Hand is modeled as a *quasi-rigid* object[5], mainly consists of pre-process and online process. The outline of the method is shown in Fig.3.

2.1.Modeling Human Hand as a Quasi-rigid Object

Quasi-rigid means that, as shown in Fig.4, when objects' surfaces undergo small deformation within the vicinity of a contact (active area), the basic shape of the overall object still keeps. In fact, our hand tissue that appear rigid visually could be modeled in this way.

2.2. Physical Model of Surface Skin Deformation

Under small deformation, skin deformation exhibits approximated linear elasticity, therefore we adopt a widely used method in contact mechanics - Boussinesq approximation as eq.1, which models the surface around a contact point as an elastic half-space [6], as the physical model. (Fig.3 A1)

$$u(\mathbf{x},\mathbf{y}) = \frac{1-\upsilon}{2\pi G}\frac{p(\mathbf{x})}{\|\mathbf{x}-\mathbf{y}\|} \tag{1}$$

where $u(\mathbf{x}, \mathbf{y})$ is the displacement at $\mathbf{y}$ due to a concentrated force at $\mathbf{x}$, v is Possion's ratio, G shear modulus, and $p(\mathbf{x})$ a concentrated compressive force applied to the normal direction at $\mathbf{x}$. The eq.1 can be rewritten by eq.2 using a polar coordinate.

$$u(r) = f(r)p, \quad f(r) = \frac{1-\upsilon}{2\pi G}\frac{1}{r}, \quad r = \|\mathbf{x}-\mathbf{y}\| \tag{2}$$

where $f(r)$ is called the system response function, r the distance between $\mathbf{x}$ and $\mathbf{y}$, p a force acting on $\mathbf{x}$.

Because of the linear elasticity assumption, the total surface displacement $u(\mathbf{y})$ due to a normal pressure distribution is defined on the surface by the integration of eq.1 over the contact surface S as eq.3.

$$u(\mathbf{y}) = \frac{1-\upsilon}{2\pi G}\int_S \frac{p(\mathbf{x})}{\|\mathbf{x}-\mathbf{y}\|}d\mathbf{x} \tag{3}$$

2.3. Volume Preserving Property in Boussinesq Approximation

Because of the approximated incompressible property of the soft tissue of human hand, the volume-preserving property need to be

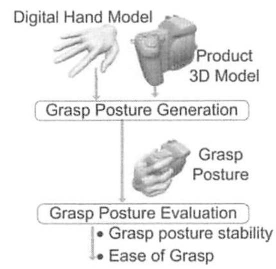


Fig.1 Grasping posture generation

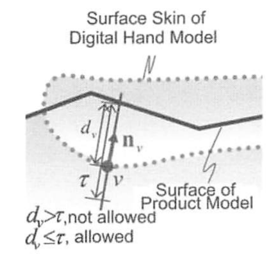


Fig.2: Collision handle scheme

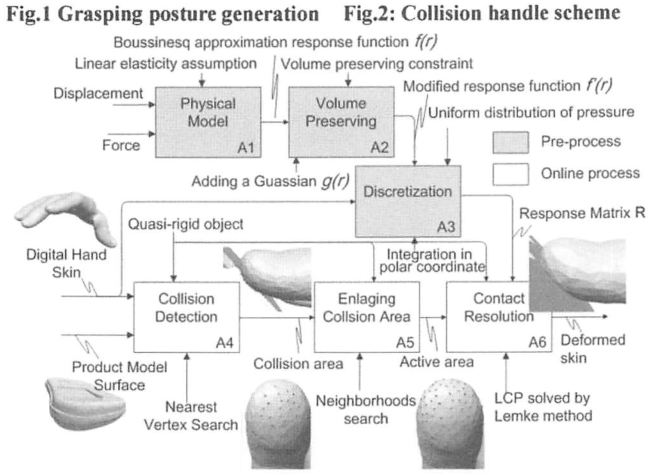


Fig.3: The proposed skin deformation method

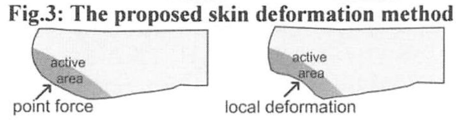


Fig.4: Conceptual model of quasi-rigid object

considered for realistic simulation. However, the original Boussinesq approximation based on the assumption of an infinite elastic half-space does not guarantee the preservation of the volume. So we realized the volume preserving property by ensuring that the deformation caused by a point force does not lead to a volume change, which can be expressed by eq.4.

$$\int_S u(\mathbf{x},\mathbf{y})d\mathbf{y} = 0 \tag{4}$$

The volume preservation can also be formulated as the following constraint on the response function $f(r)$ in polar coordinate:

$$\int_0^\infty f(r)rdr = 0 \tag{5}$$

As shown in Fig.5, a plausible analytical response function with volume preserving can be obtained by adding a Gaussian function to the original response function $f(r)$ in the opposite direction as

$$f'(r) = f(r) + (-g(r)) = f(r) + (-a\exp(-r^2/2c^2)) \tag{6}$$

where $f'(r)$ is the modified response function, $g(r)$ the Gaussian function, a the height of Gaussian, c the width of Gaussian. Fig.5 shows shapes of $f(r)$, $g(r)$, and $f'(r)$.

2.4. Discretization

When using a triangular mesh as the Digital Hand, the discrete setting of eq.3 is needed. The response relation R_{ij} between the displacement u_i that vertex $\mathbf{q}_i$ experiences and the pressures p_j acting on vertex $\mathbf{q}_j$ can be expressed in matrix form in eq.7,

$$\mathbf{u} = \mathbf{R}\mathbf{p} \tag{7}$$

where $\mathbf{u} = [u_1 \cdots u_N]$ is the vector of displacements, $\mathbf{p} = [p_1 \cdots p_N]$ the corresponding normal pressures, and $\mathbf{R} = \{R_{ij}\}$ the system response matrix.

Since a triangle mesh model is used in our study, we simplified the pressure distribution as an uniform distribution on a triangle to calculate each entry of **R** by the integration in polar coordinate as:

$$R_{ij} = \tfrac{1}{3}\iint_{S_j} f'(r)rdrd\theta = \tfrac{1}{3}\left(\iint_{S_j} f(r)rdrd\theta - \iint_{S_j} g(r)rdrd\theta\right) \tag{8}$$

where $S_j = S_{1_j} + \ldots + S_{N_j}$, each of which is the area of the triangles of the first ring neighborhood of $\mathbf{q}_j$. The integration of $f(r)$ can be analytically solved by algebraic addition of the integration of six right-angle triangles (see pp. 53 - 55 of [6] for details), and the one of $g(r)$ also is analytical. For the same Digital Hand, we can pre-compute all entries of **R**, as a pre-process(Fig.3 A3).

2.5. Collision Detection and Active Area

During a simulation, Digital Hand might collide with a product surface, and intersect each other. To resolve the contact, we need to find a local deformation on Digital Hand, such that the hand both touches the product surface without interpenetration. For achieving it, first, we detect whether the two models collide. If a collision is found, we enlarge the collision area to the active vertices area where the surface vertices potentially experience displacements due to the deformation that resolves the intersection.

We use a collision detection algorithm presented in [1] which uses the nearest vertex search and the signed distance function (Fig.3 A4). Once collision areas are found, by neighborhood query based on mesh model, we define an active area as the union of the collision area and its local three ring neighborhood (Fig.3 A5).

2.6. Contact Resolution using LCP

Our goal is to realize the deformed surface caused by a contact without interpenetration. As shown in Fig.6, first, on the contact area, $\mathbf{p}^{H} = \mathbf{p}^{P}$, where $\mathbf{p}^{H}$, $\mathbf{p}^{P}$ respectively denote a vector of pressures on the surface of Digital Hand and the product model. In addition, we define a "separation" of two corresponding vertex $\mathbf{q}_i^{H}$ and $\mathbf{q}_i^{P}$ as $s_i = u_i^{H} + u_i^{P} + \sigma_i \|\mathbf{q}_i^{H} - \mathbf{q}_i^{P}\|$, where $\sigma_i = -1$, if $\mathbf{q}_i^{H}$ intersects the volume bounded by product model, and $\sigma_i = 1$, if no interpenetration occurs. From observation, the pressures and the separations are complementary, i.e., at each vertex, at least one of them is zero, which can be reduced to a Linear Complementarity Problem(LCP) as follows,

$$\mathbf{s} = \mathbf{R}\mathbf{p} + \mathbf{q},\ \mathbf{s} \geq \mathbf{0},\ \mathbf{p} \geq \mathbf{0},\ \mathbf{s}^{\mathrm{T}}\mathbf{p} = \mathbf{0} \tag{9}$$

where $\mathbf{s}=[s_1 \cdots s_N]^T$, $\mathbf{R} = \mathbf{R}^{H} + \mathbf{R}^{P}$, $\mathbf{q} = [\sigma_1\|\mathbf{q}_1^{H} - \mathbf{q}_1^{P}\| \cdots \sigma_N\|\mathbf{q}_N^{H} - \mathbf{q}_N^{P}\|]^T$ is initial separation, and superscripts H and P stand for Digital Hand and product model. In our study, the product models are regarded as rigid objects, therefore the LCP can be simplified: $\mathbf{R} = \mathbf{R}^{H}$, $\mathbf{q} = [\sigma_1\|\mathbf{q}_1^{H}\| \cdots \sigma_N\|\mathbf{q}_N^{H}\|]^T$. Finally by solving the LCP using Lemke's method, we can find the displacement and pressure at each vertex to realize the surface skin deformation caused by a contact and to estimate the force acting on contact surface (Fig.3 A6).

3. Results and Discussion

By referring to a survey paper [7], we choose $G = 60\times10^3$ Pa , $v = 0.5$, $a = 0.8$mm, and $c = 5$mm. The typical pre-process time for one finger (e.g. middle finger, about 1500 vertices) is about 340s (Intel Core i7, 6GB main memory). An illustration for contact resolution result (middle finger) whose maximum penetration depth is 1.12 mm is given in Fig.7. The computations took 4835ms for the collision detection, and 438ms for contact resolution. We can see the fingertip touches the surface of product model without any interpenetration. In the front and back part of the contact area, there are two small bulges resulting from the proposed volume preserving property. Fig.8 shows the relations between the specified maximum penetration depth and the contact area/ the contact surface force. The results indicated they have approximately linear relationships. The computation times for collision detection were about 4800ms, and the one for contact resolution varied from 111ms to 2111ms.

But to relatively low density Digital Hand, in a larger penetration depth, the deformed skins are not sufficiently smooth for the observation. Therefore, we increased the number of vertices of Digital Hand about 4 times (about 5.3×10^4 vertices). The deformation results of the fingertip and the palm in different maximum penetration

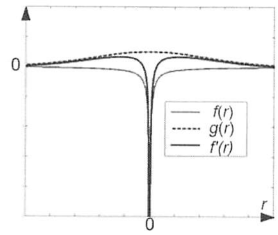


Fig.5: System response functions

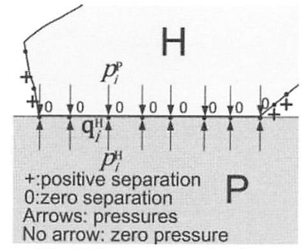


Fig.6 Contact resolution

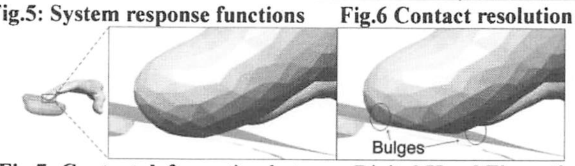


Fig.7: Contact deformation between Digital Hand Fingertip and product model surface (penetration depth = 1.12mm)

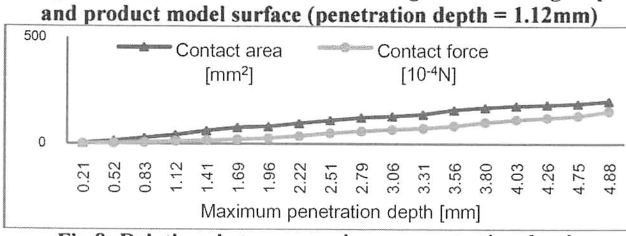


Fig.8: Relations between maximum penetration depth and contact area/ contact force

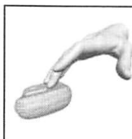
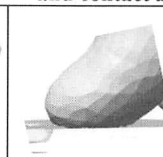
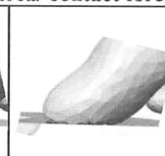
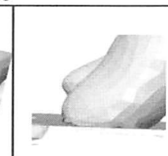
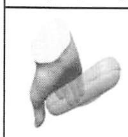
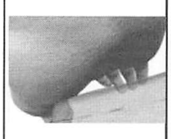
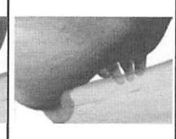
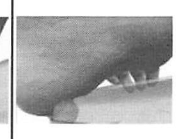
 Fingertip			
Depth[mm]	1.46	1.98	2.80
 Palm			
Depth[mm]	1.51	3.20	4.88

Fig.9: Deformed skins in the Digital Hand model with increased density

depth are shown in Fig.9. The relatively smooth deformed skins can be observed.

The overall rigidity and local deformability of quasi-rigid object used by this research are valuable for integrating such contact skin deformation scheme with the existing Digital Hand model where a skin deformation around the bent finger joints are already implemented[1][4].

The current proposed method still have some problems on the selection of Possion's ratio and shear modulus at different parts and depths in the hand tissues, and of the appropriate height and width of the Gaussian function in assembling the response matrix. The future work includes solving these problems and the experimental verifications.

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