

Optimization-Based Grasp Posture Generation Method of Digital Hand for Virtual Ergonomics Assessment

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ABSTRACT

Automatically generating humanlike grasp postures of the digital hand is a key issue for the virtual ergonomic assessment of the industrial products. In this paper we propose a new optimization-based approach for generating the realistic grasp posture. As an objective function, we use the number of the contact points, the fit of the specific part of the hand surface for the feature edges of the product surface and the margin for the constraints on the joint angle limits of the figures. The experimental studies on the grasp posture generation for the digital camera indicate that more realistic grasp posture could be generated using the proposed optimization-based method than the one using our former method.

INTRODUCTION

Recently, the manufactures of handheld information appliances have had to refocus their attention on the ergonomic design in order to differentiate their products and to gain competitiveness in the market. The ergonomic design of information appliances can be separated into two main categories: physical and cognitive. The physical aspect of the ergonomic design of these appliances includes easiness of grasping the housing, relevance of arranging the positions of physical components (buttons, switches, dials, displays lumps etc.) on the user-interface, and the ease of their manipulations. The assessment of the physical aspect usually requires subjects to test the physical mockups of the appliance.

However, the cost of fabricating the physical mockups usually becomes expensive, and its fabrication takes a long time. The manufacturer would like to cut these

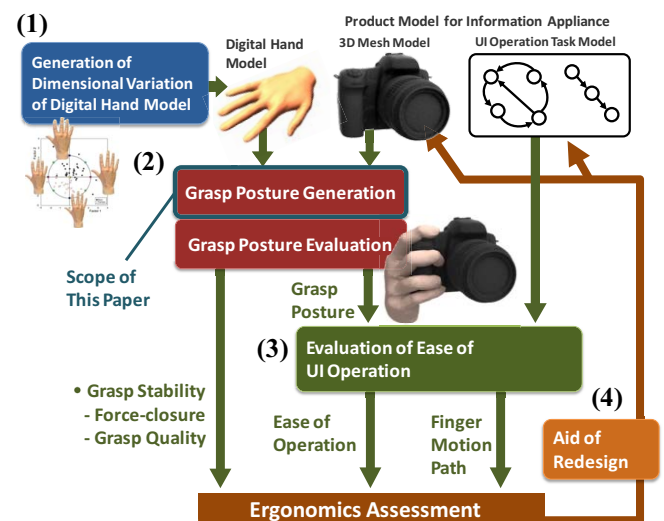


Figure 1. The overview of our proposed ergonomic assessment system

costs and decrease the development period while taking the ergonomic design of the product into consideration.

To cut these costs and to decrease the developmental period, many 3-D CAD systems have spread widely to the design process of these information appliances. And the 3-D digital mockup of the housing of the appliances can be easily obtained in the early design stage. So there is a strong possibility that we can execute the ergonomic assessments by integrating digital human models, especially including the digital hand models, with digital mockups of the appliances to decrease the extra time and cost of making physical mockups.

Some simulation software using digital human models has been commercialized [1] and is being used in the design of automobiles and airplanes. However, the digital hand models included in these human models of such software do not necessarily comply with the

desired accuracy and size variation of human hands when evaluating the relevance of grasping and operating the handheld appliances.

Therefore, the purpose of our research is to develop a virtual ergonomic assessment system for designing handheld information appliances by integrating the digital hand model with the 3-dimensional product model of the appliance.

As shown in Figure 1, in our system, we realize the following features and functions necessary for ergonomic assessment:

1. Generation of kinematically and geometrically accurate 3-dimensional digital hand models with rich dimensional variation: We apply a digital hand model called “Dhaiba-Hand” [4] to the ergonomic assessment in our system. The Dhaiba-Hand was developed by DHRC, AIST, JAPAN. The Dhaiba-Hand has a very precise hand link structure model which is derived from the kinematic analysis for the measured data obtained from motion capture and MRI[2,3]. 3-D digital hand models with dimensional variation can be generated by deforming a generic hand model which has been created by the factor analysis of dimensional measurements taken from 103 Japanese subjects’ hands [4].
2. Automatic generation and evaluation of the grasp posture: By only inputting a few user-interactions, our system automatically generates one of the possible grasp postures determined by the product shape and the digital hand geometry. It also quantitatively evaluates the indices of the grasp stability for the product geometry, which is calculated based on the force-closure and the grasp quality used in the grasp planning of robotics.
3. Automatic evaluation of ease of the finger motions in operating the user interface: The system automatically moves fingers of the digital hand by following an operation task model of the user-interface (e.g. which button has to be pushed). It also automatically evaluates ease of finger motions during operation of the user interface based on the flexion joint angles of fingers.
4. Aiding the designers to redesign the housing shapes and to change the placement of the physical components of user-interfaces (e.g. buttons, dials, displays) in the digital mockup: By the above two evaluation indices, the system conducts sensitivity analysis of these indices for some dimensional parameters of the housing. This analysis finds an optimal combination of some dimensional parameters of the housing shapes so as to maximize the evaluation indices for the grasp posture.

In this paper we mainly describe the above function 2, especially the function of generating the grasp posture.

RELATED WORKS

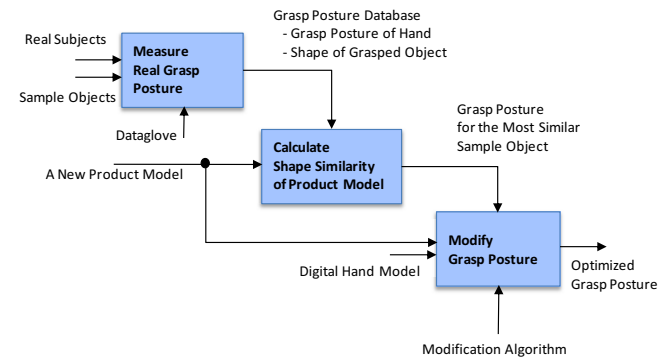
APPLICATION OF DIGITAL HAND IN ROBOTICS, VIRTUAL REALITY, AND COMPUTER GRAPHICS

Many researchers in robotics, virtual reality (VR), and computer graphics have proposed in applications for the digital hand model: a grasp planning system for robotic hand design [6,7], a VR environment for directly operating the virtual objects [9], a motion simulator for playing a music instrument [10], or a grasp posture generator for computer animation [11].

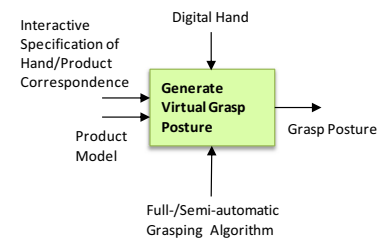
However, as described in our previous paper [18], these related works on the digital hand were not necessarily applicable to the ergonomic assessment of handheld information appliances because of the lack of accuracy of the model.

MEASUREMENT AND MODEL CONSTRUCTION OF A HUMAN HAND IN ANTHROPOMETRY

In anthropometry, Kouchi [4] developed a generation method of geometrically accurate digital hand models with rich dimensional size variation. These hand models can be generated by deforming a generic hand model which has been created by the factor analysis of dimensional measurements taken from 103 Japanese subjects’ hands. Miyata [8] developed a generation method for a precise hand link structure model which is derived from the kinematic analysis for the measured data obtained from motion capture and MRI. These methods are implemented as “Dhaiba-Hand” [4] which is



(a) A variant method



(b) A generative method

Figure 2. The comparison of the grasp posture generation methods of the related works.

a part of the full-body digital human modeling project “Dhaiba” [19].

GENERATION AND EVALUATION OF GRASP POSTURE

Some research [6,20,21,18,11,17] has proposed the generation and evaluation method of the grasp postures of the digital hand for the objects. As shown in Figure 2(a)(b), the representative approaches for generating the grasp posture are roughly classified into two types: a variant method [11,17] and a generative method [6,20,18].

In the variant method, the real grasp postures of many subjects for sample objects have been measured in advance using a dataglove to build a grasp posture database. Then, in the generations step, one grasp posture whose object shape is most similar to the given object model shape is chosen from the grasp posture database. The selected posture is modified to match the product model shape. If a very similar product shape can

be found in the database, a nearly appropriate grasp posture for the given product can be obtained after this modification process.

On the other hand, in the generative method, the grasp posture is generated by a full-/semi-automatic grasping algorithm. It does not need any database of real grasp postures. For any unknown shape, this method can generate a grasp posture that satisfies geometric conditions when the hand is contacting with the product surface.

However in related works using both methods, there have been some problems in regards to obtaining ideal grasping conditions in information appliances. For example, the variant method of Li [17] cannot generate the posture when their hand posture database does not include the shape of the product similar to a new one. On the other hand, our previous work [18] using the generative method sometimes fails to generate a desired grasp posture. The user needs to predict a few combinations of the user-input points which results in the successful grasp. However, it is difficult for the user to prospect the final grasp posture at input (see the section 3.4 for more detail). And, both of these researches did not discuss whether the obtained grasp postures were truly appropriate and possibly realistic one or not from the experiments.

OUR PREVIOUS WORK

DIGITAL HAND MODEL

To perform effective digital ergonomic assessment, it is insufficient to use only one digital hand model with a fixed dimension because the physical dimensions of the appliance users differ from person to person. Therefore, we needed to generate a digital hand model with possible anthropometric variation. In order to achieve this purpose, we used a digital hand model based on the Dhaiba-Hand [4]. The digital hand model used in our system consists of the following four parts and the relationship among these parts is shown in Figure 3(b):

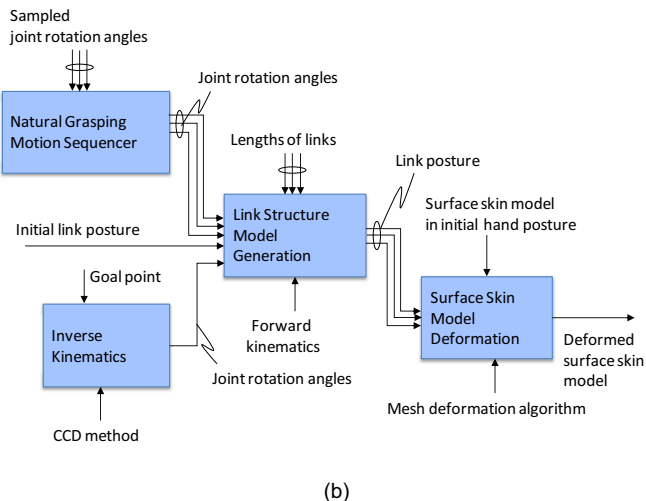
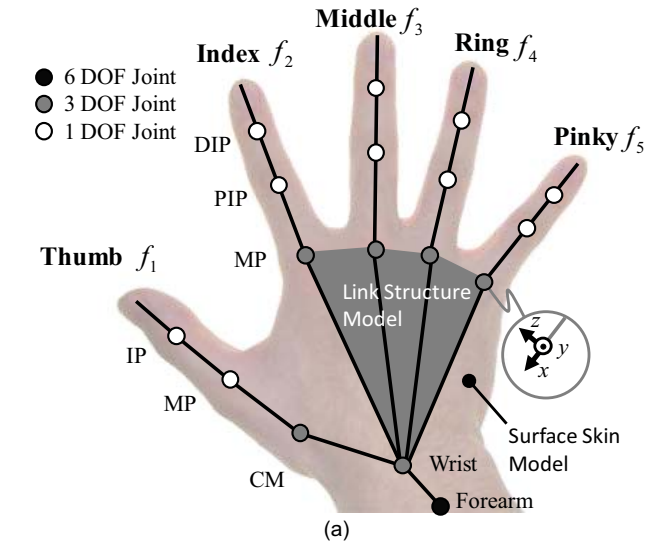


Figure 3. The digital hand model of our system. (a) The link structure model, (b) The flow of the deformation of the surface skin model.

1. **Link structure model:** A link structure model approximates the rotational motion of bones in the hand. The model was constructed from the measurement by MRI and the motion capture. The model has 17 links, and each link has two joints at both its ends. These joints can rotate with 1, 3 or 6 degrees of freedom, as shown in Figure 3(a).
2. **Surface skin model:** A surface skin model is a 3-dimensional polygonal mesh for the hand surface generated from CT images, as shown in Figure 3(a). The geometry of the skin model is defined at only one opened posture.
3. **Surface skin deformation algorithm:** This algorithm defines the deformed geometry of the surface skin

model when the posture of the link structure model is changed, as shown in Figure 3(b).

4. **Finger closing motion sequencer:** The finger closing motion sequencer's function is to automatically and naturally generate a finger-closing motion path of the hand model from a fully opened state to a clenched one, as shown in Figure 3(b). This motion reflects the joint angle constraints of the link structure model.

A link structure and a surface skin model are generated by inputting the 82 dimensional parameters of a specified subject's hand into the *generic hand model* which are implemented in the Dhaiba-Hand [4]. On the other hand, a surface skin deformation algorithm and a natural grasping motion generator were originally developed by us [18].

GRASP POSTURE GENERATION

The generation of the grasp posture of the digital hand model for the product shape model is the first step in our system. As shown in Figure 4, the process consists of four phases: 1) selection of the contact point candidates, 2) generation of the rough grasp posture, 3) optional correction of the contact points, and 4) maximization of the number of the contact points.

EVALUATION OF THE GRASP STABILITY

After generating the grasp posture, the system automatically evaluates the grasp stability for the product in this estimated posture. We introduce the *force-closure* and the *grasp quality* into the evaluation of the grasp stability.

Originally, in the definition of robotics grasping, a grasp is said to be force-closure if it is possible to apply forces and moments at the contact points such that any external force and moments acting on a grasped object can be balanced [15]. Then, a grasp quality is defined as "the reciprocal of the sum of magnitudes of contact normal forces required to achieve the worst case wrench" [16].

In our system, the force-closure condition indicates whether the digital hand can grasp the product model

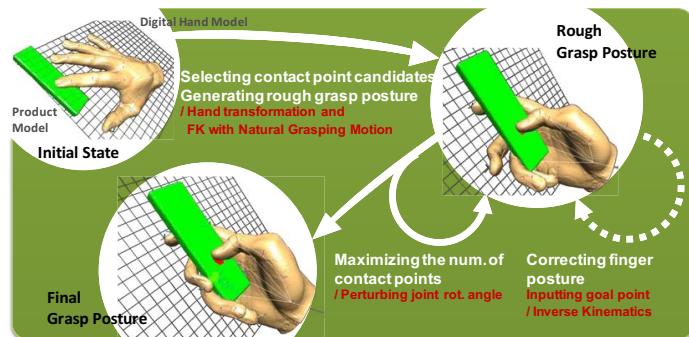


Figure 4. The algorithm of our previous grasp posture generation method

stably at the contact points between the digital hand and the product model. Moreover, if an estimated grasp posture can satisfy the force-closure, grasp quality can express how stably we can hold the product at this posture.

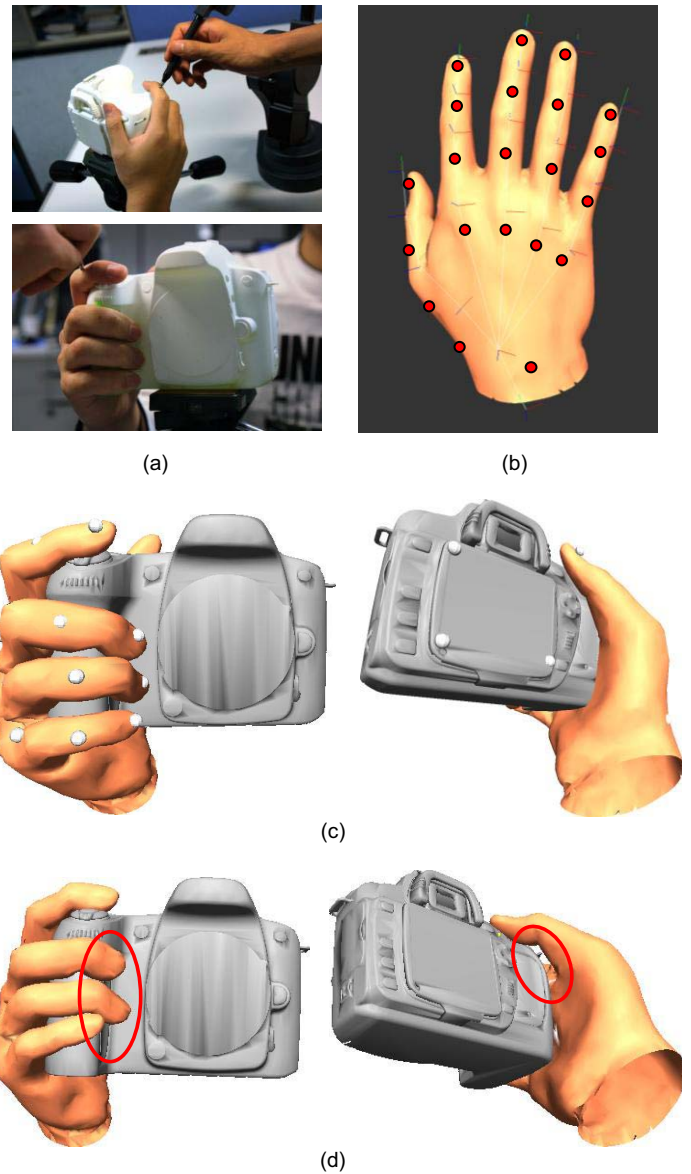


Figure 5. The grasp postures for a SLR. (a) The real grasp posture of a real subject, (b) measured feature points on hand surface by the digitizer (red points), (c) the reconstructed posture from a real subject's grasp and (d) the result of our previous system.

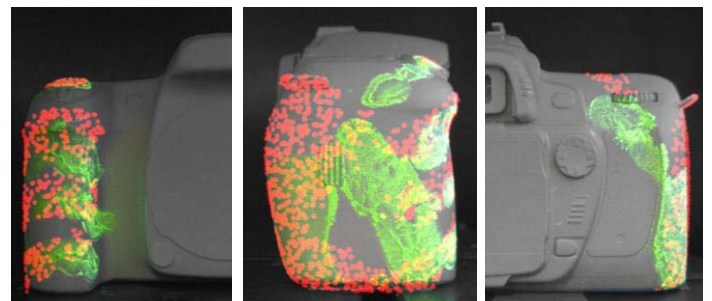


Figure 6. The contact area on the product. Green area was painted when a real subject grasped the product, and superimposed red points are contact points of system-generated grasp posture.

PROBLEMS ON GRASP POSTURE GENERATION

Figure 5-6 shows the results of the verification for the grasp posture generation method in our previous work. We used three types of digital single lens reflexes (SLR) and eight real subjects for the test. Figure 5(a) shows the real grasp posture of a real subject and Figure 5(c) shows the reconstructed posture on the system. The joint angles of this posture were acquired by fitting some feature points on the digital hand surface (Figure 5(b)) to the corresponding points on the real hand surface which were measured by using a 3D digitizer “MicroScribe” [5]. The position and the orientation of the product model were reconstructed in the same way. On the other hand, Figure 5(d) shows the one generated by our previous grasp posture generation method. The digital hand in Figure 5(d) is almost the same size as one of the subject’s in Figure 5(c). Figure 6 shows the comparison of the contact area on the product between the grasp posture of the real subject and the one that was system-generated. The contact area where the subject touched is shown in green paint and the one where the digital hand touched in the system-generated posture is shown as red points. From these figures, we found several differences points between these two postures:

1. The fingertips for the fingers (III)-(V) in the system-generated posture could not reach the lens-side face of the grip of the SLR (see the left portion of Figure 5(d)).
2. The surface around the IP and MP joint of Thumb in the system-generated posture could not fit to the product surface (see the right portion of Figure 5(d)).
3. The palm in the system-generated posture and the one in the subject’s grasp touched rather different area on the product surface. This indicates that these two postures have different hand orientations with respect to the SLR housing (see the middle portion of Figure 6).

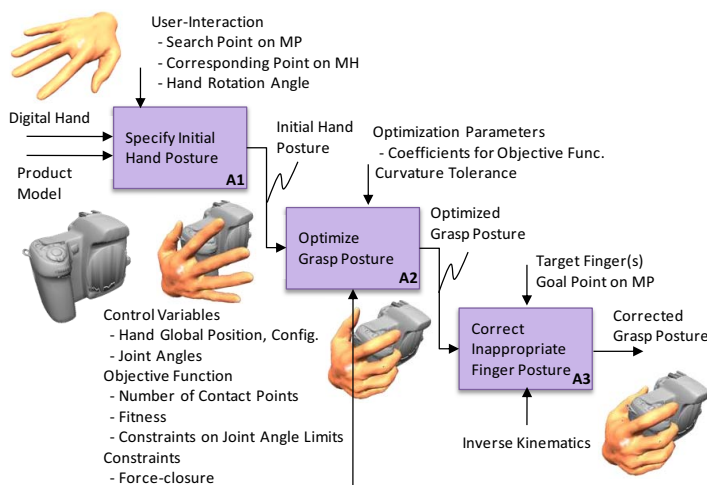


Figure 7. The algorithm of our new grasp posture generation method

These differences between the real grasp posture and the system-generated one may cause wrong results in our virtual ergonomic assessment system. Actually, from results of other interview-based test which investigates what are the points of view of the ergonomic assessment for the SLR users, we found that real subjects felt that the system-generated postures had less sense of a “tight fit” than the real grasp ones. Moreover, we found that this sense of “tight fit” heavily affects the ergonomic evaluation for a specific type of the product models, such as SLRs.

Therefore, in this paper, we propose a new improved method for generating more humanlike grasp posture for these product models.

PROPOSED OPTIMIZATION-BASED METHOD FOR GRASP POSTURE GENERATION

OVERVIEW

Figure 7 shows the overview of our proposed optimization-based improved method for generating the grasp posture. In the process of generating a grasp posture, finding the appropriate position and orientation of the hand is a critical problem. The hand posture whose position and orientation are globally optimized is not always the most humanlike or realistic one. So, we need to generate a posture by a local optimization method which limitedly searches for the optimal grasp posture around a user-defined initial position and orientation of the hand. At the beginning of our grasp posture generation method, the user of the system specifies the rough position and the rough orientation of the hand by some user-interactions (A1). Then next, we locally optimize the hand posture by perturbing the position, orientation and joint angles of the hand only limited among the initial hand posture where the objective function which is to be maximized consists of the number of the contact points, the degree of fit between the feature area of the product and finger surface, and the penalty of the constraints on the joint angle limits of the fingers. (A2). Finally we optionally correct the inappropriate finger postures by inverse kinematics (A3).

INITIAL HAND POSTURE SPECIFICATION

First, as shown in Figure 8(a), the user selects two points. One is the search point p_s in the set of points C which are randomly generated on the surface mesh M^p of the product model. The other is a vertex v_b on the surface mesh M^d of the digital hand. And also, the user specifies a hand rotation angle θ_s around the normal \mathbf{n}_{p_s} . From these user-interactions, an initial hand posture is generated by the system as follows:

1. The system sets the hand posture to an open state (All joint angles of the hand are set to zero).

2. The system translates M^H so that v_h is identical to p_s .
3. The system rotates M^H so that the normal vector \mathbf{n}_{vh} of the vertex v_h is identical to the normal $-\mathbf{n}_{ps}$ of the point p_s .
4. The system rotates M^H by θ_s around the normal vector \mathbf{n}_{ps} of search point p_s .
5. The system perturbs the position and the orientation of M^H to maximize the number of contact points between M^H and M^P .

GRASP POSTURE OPTIMIZATION

After the initial hand posture generation, the posture is still in its open state. So, in the next step, we locally optimize the grasp posture by perturbing the relative position and orientation and by closing each finger to maximize the objective function. This optimization process is described as the following:

Control Variables

1. Roll, pitch and yaw angle for the hand rotation. The center of this rotation is the point p_s .
2. Distance for the hand translation. The direction of this translation is limited to the normal vector \mathbf{n}_{ps} .
3. Joint angles of the hand. We use MP, PIP and DIP joint of Index, Middle, Ring, and Pinky finger (see Figure 3).

Objective Function

We define the objective function as

$$f(\mathbf{x}) = w_{Nc} f_{Nc}(\mathbf{x}) + w_{fit} f_{fit}(\mathbf{x}) - w_{joint} f_{joint}(\mathbf{x}) \quad (1)$$

Where \mathbf{x} is the 20 dimensional vector of the control variables. w_{Nc} , w_{fit} and w_{joint} are the positive coefficient of each term. f_{Nc} , f_{fit} and f_{joint} are defined as follows:

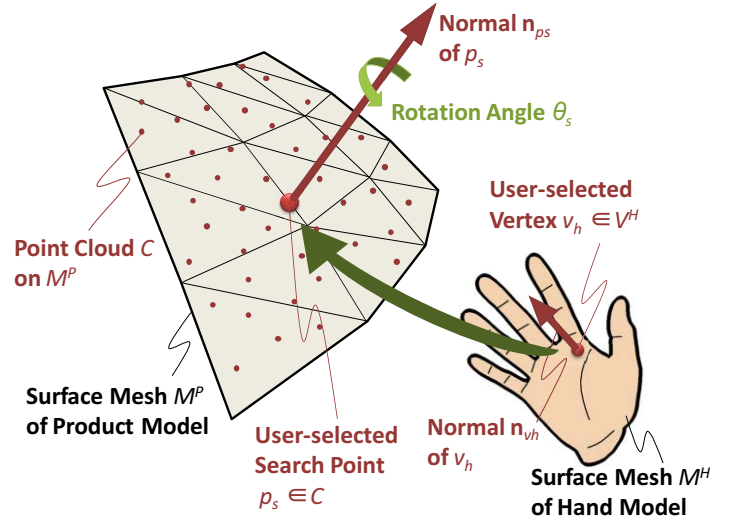
1. f_{Nc} is the number of the contact points between M^H and M^P .
2. f_{fit} represents the degree of fit between the feature edges of the product surface and the feature area of the finger surface and is defined as

$$f_{fit} \equiv \sum_{p \in P_{Contact}} \kappa(p) Featur\&Nearer\&(p, M^H) \quad (2)$$

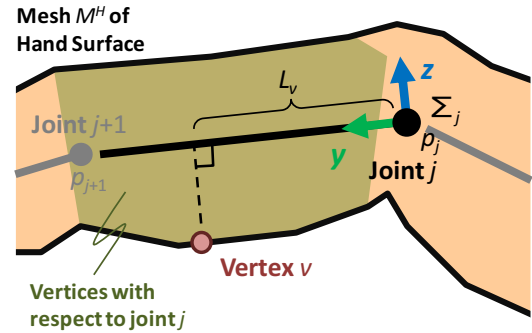
Where p is the contact point in the contact point set $P_{Contact} \in C$, $\kappa(p) \in \{0,1\}$ is the absolute curvature of the point p , which is normalized by the maximum value of the $\kappa(p)$ and binarize by the user-defined tolerance τ . $Nearest(p, M^H)$ returns the nearest vertex on the hand mesh surface M^H for the point p . $Featur\&\in[0,1]$ returns pre-defined value of the hand vertex feature. As shown in Figure 8(b), we defined the value of the hand vertex feature as

$$Featur\&(v) = \begin{cases} L_v & (L_v \leq 0.5) \\ 1 - L_v & (L_v > 0.5) \end{cases} \quad (3)$$

$$L_v = Dist_{jv}(v, p_j) / Dist_{jv}(p_j, p_{j+1})$$



(a) Initial hand posture specification



(b) Definition of L_v

Figure 8 Grasp posture optimization method.

Where p_j is the origin of the coordinate system Σ_j attached to the joint j . Every vertex v on the fingers is assigned to a particular joint j . $j+1$ represents the child joint of the joint j . $Dist_{jv}(p_1, p_2)$ is the distance between the point p_1 and p_2 along the y axis direction of the local coordinate system Σ_j attached to the joint j , shown in Figure 8(b).

3. f_{joint} represents the penalty of the constraints on the joint angle limits and the joint angle dependency of the hand, and is defined as follows:

$$f_{joint} = \sum_{i \in \{Middle, Ring, Pinky\}} \sum_{j \in \{DIP, MP, MPz\}} w_j s_j(i) + w_{PIP}^x \left(\max(\theta_{PIP(Middle)}^x, \theta_{PIP(Ring)}^x, \theta_{PIP(Pinky)}^x) - \min(\theta_{PIP(Middle)}^x, \theta_{PIP(Ring)}^x, \theta_{PIP(Pinky)}^x) \right) \quad (4)$$

Where

$$s_{DIP}^x(i) = \left| \theta_{DIP(i)}^x - (2/3)\theta_{PIP(i)}^x \right|$$

$$s_{MP}^x(i) = \max(\theta_{MP(i)}^x - dmax(\theta_{MP(i)}^x), dmin(\theta_{MP(i)}^x) - \theta_{MP(i)}^x) \quad (5)$$

$$s_{MP}^z(i) = \max(\theta_{MP(i)}^z - dmax(\theta_{MP(i)}^z), dmin(\theta_{MP(i)}^z) - \theta_{MP(i)}^z)$$

$\theta_{j(i)}$ is the angle of joint j of finger i . $dmax()$, $dmin()$ is the maximum and the minimum dynamic joint angle limit, which is determined by the static joint

angle limit and the joint angles of the neighboring fingers (see [13] for more detail). w_j is the weight imposed on each constraints.

Constraints

1. The grasp posture must satisfy the force-closure.
2. All joint angles must satisfy the static joint angle limits [13].

Algorithm

The system finds the optimized grasp posture which has the maximum value of the objective function by exhaustively searching all possible combinations of the control variables around the initial hand posture.

OPTIONAL CORRECTION OF THE FINGER POSTURE

The optimized grasp posture obtained in the previous section may include the fingers with inappropriate postures which are different from the ones in operating the user-interface of the product. In such cases, the user of the system can optionally correct these inappropriate postures of the fingers by additionally selecting a goal position to which the fingertip should move on the surface of the product model. The corrected posture for the goal position is found by solving the inverse kinematics using the CCD (Cyclic-Coordinate Descent) method [14].

RESULTS

Figure 9 shows the results of our proposed grasp posture generation method and Table 1 shows the user-defined parameters used for the optimization. We found the appropriate postures of the Index, Middle, Ring, and Pinky joints using the optimization (Figure 9(d)), and the Thumb posture was determined by manual correction (Figure 9(e)(f)(g)). The total processing time was 2min48s.

Figure 10 shows the comparison of the finger joint angles of the real grasp postures with the ones of the system generated postures. The nearest postures for each system generated posture are both the posture of subject 8. The average error of the finger joint angles generated by our previous method and the one by our proposed method for the ones of subject 8 are 12.7[deg] and 11.3[deg], respectively. The posture of our proposed method had a fewer errors than the one in our previous method. We used the digital hand which has the representative adult average size for these tests and the subject 4, 5, 8 has the approximately same size of this average digital hand.

Figure 11 shows the contact area on the product based on the result obtained from the optimization (red points). The green area was painted when a subject grasped the product (the same grasp as Figure 6). The objective function value of the optimized posture is 169.0

($f_{Nc} = 532$, $f_{fit} = 27.0$ and $f_{joint} = 60.0$). From these figures, we can find some improvements on the grasp posture obtained from the previous method as follows:

1. The fingertips for the finger (III)-(V) in the system-generated posture could reach the lens-side face of the grip of the SLR (See Figure 9(f) and the left portion of Figure 11).
2. The surface around the IP and MP joint of the Thumb in the system-generated posture could fit to the product surface (see Figure 9(g)).
3. Palm in the system-generated posture and the one in

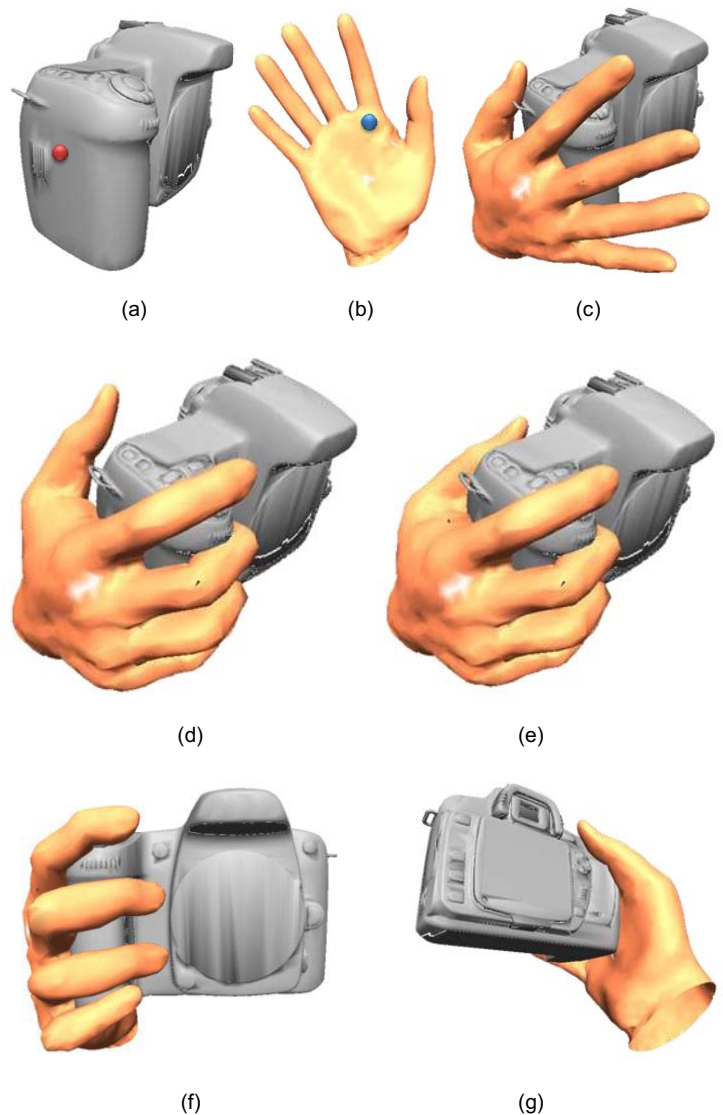


Figure 9. Results of our new grasp posture generation method. The red point of (a) shows the search point on the product and the blue point of (b) shows the corresponding point on the hand. (c) Initial hand posture, (d) optimized grasp posture and (e) (f) (g) corrected grasp posture (Thumb posture was corrected).

Table 1. User-defined parameters

| | | | |
|----------------------------|------|------------------------|-----|
| Curvature Tolerance τ | 0.17 | Coefficient w_{MPx} | 80 |
| Coefficient w_{Nc} | 0.3 | Coefficient w_{DIPx} | 150 |
| Coefficient w_{fit} | 1.0 | Coefficient w_{MPz} | 50 |
| Coefficient w_{joint} | -0.3 | Coefficient w_{PIPz} | 20 |

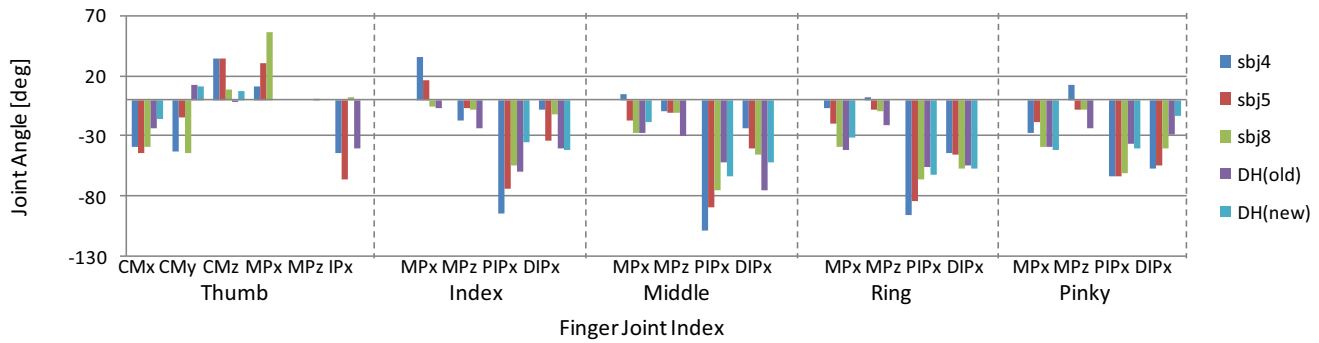


Figure 10. The comparison of the finger joint angles of the real grasp postures (sbj4,5,8) with the ones of the system generated postures (DH(old) and DH(new)). The posture of DH(old) was generated by our previous method, and the one of DH(new) is done by our proposed method.

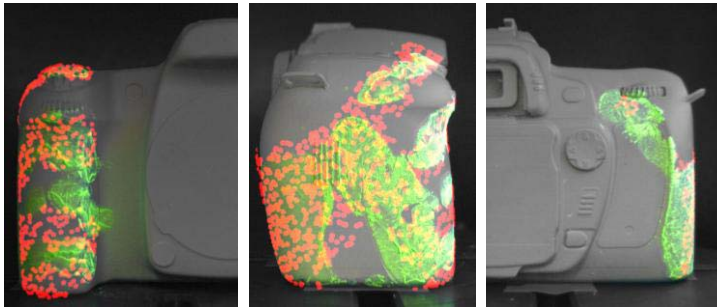


Figure 11. Contact area on the product by using the proposed method by using the proposed method

the subject's grasp touched almost the same area on the product surface. This indicates that these two postures have almost the same hand orientation with respect to the SLR housing (see Figure 9(e)).

In order to analyze the effect of three terms in the objective function of eq.(1), we compared generated grasp postures, where we used only single term of the objective function in the optimization process, as shown in Figure 12. These grasp postures did not seem to be realistic in holding the SLR. So we could find that we must use all three terms of the objective function and set weight coefficients to proper values in order to obtain realistic grasp postures. Currently we have found that the coefficients where the term of $w_{Nc} \cdot f_{Nc}$ is a little bit larger than the other terms results good postures.

We validated the proposed method by using five

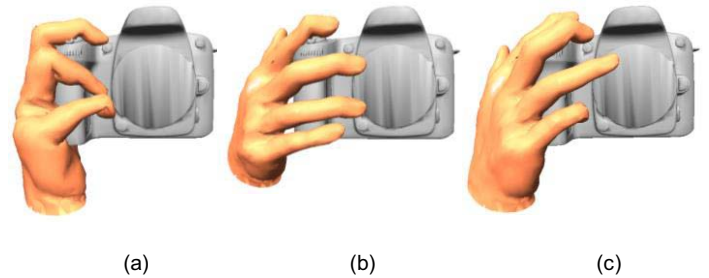


Figure 12. The results of our new grasp posture generation method where only single term ((a) f_{Nc} , (b) f_{fit} and (c) f_{joint}) of the objective function was used in the optimization process.

subjects, as shown in Table 2. We let each subject reenact the grasp postures generated by the previous and the proposed method from the system, and asked them which grasp posture gave them a sense of "tighter fit". As the result, all subjects answered that the grasp posture generated by the proposed method gave them a sense of "tighter fit". This result indicates that proposed grasp posture is valid to some extent.

CONCLUSIONS

The conclusions of our research are summarized as follows:

1. We proposed a system of automatic ergonomic assessment for handheld information appliances by integrating the digital hand model with the 3-dimensional product model of the appliances.

Table 2. Validation of the proposed method

| Subject | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Subjects reenacted the grasp postures generated by the previous method. | | | | | |
| Subjects reenacted the grasp postures generated by the proposed method. | | | | | |

2. We proposed an improved method of semi-automatically generating the grasp posture of the digital hand for the product model using an optimization method and inverse kinematics. As the objective function for the optimization, we used the number of the contact points, the degree of fit between the feature area of the product and the hand, and the constraints on the joint angle limits of the fingers. From the experiment of grasp generation for a commercial model of a SLR housing, we could find that this optimization-based method could automatically generate more accurate and more realistic grasp posture than the previous method did.

In our future research, we will extend our optimization-based method which can avoid obtaining the locally optimized grasp and can correct the finger postures by using the inverse kinematics in the optimization process. We would like to develop a new function to evaluate the ease of finger operation for the use-interface of the products, and to aid the designers in redesigning the housing shapes and the user-interfaces in the product model.

ACKNOWLEDGEMENT

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