3D Modeling of Human Hand with Motion Constraints

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Abstract

This paper describes a new approach for modeling of the human hand by considering the dynamics and the natural constraints of hand motion hand shape. The hand model consists of a dynamic model and a surface model. The dynamic model is used to generate the posture of the hand. We have shown that natural hand posture can be generated even when only a few hand parameters are used. The surface model is used to generate the hand shape based on the posture obtained from the dynamic model. The surface model is based on the digitized 3D shape of a real hand.

1. Introduction

Hand animation is complicated and difficult since there are so many degrees of freedom of the hand. To generate a particular hand posture, one has to give more than 27 parameters of the hand joints [2]. Recently, motion captors such as data gloves have been used to capture the motion sequence of the hand and use it for hand animation. Although the hand animation generated in this way is smooth and natural, it can only recreate the sampled hand motion, and will not be able to be used in a completely computer synthesized hand animation system. Even if there are many degrees of freedom in a human hand, the finger motion is not completely independent [2, 3]. The angle of each hand joint is influenced by the angle of the neighboring joints and the ones of the adjacent fingers joints. We try to describe the relation between the joints in one finger and the relation between the motions in other fingers. We will then use this information in a dynamic model description. When we want to generate a particular posture of hand with this model, we give "force" to the finger we want to move. The posture of one or several of the fingers with given "force" is first determined with the model. This posture is then used with the dynamic model to determine the posture of the other fingers.If one can obseve the posture of some of the fingers only the model can be used to predict the posture of the other fingers. The unknown posture parameters of the hand can be determined by the known parameters and the dynamic model by considering the "inner" force between fingers. A surface model of the hand is also built for generating images of a hand that looks real. Once the hand posture is determined by the dynamic model, the posture parameters are used to change position of the control points of the surface model to determine the shape of the surface of the hand. Then the texture mapping technique is used to generate the hand images for animation.

2. Skeleton model

The structure of the skeleton model is based on the anatomical respcts. We modeled the hand skeleton with right number of links and joints. The links have no deformation but we prepared enough number of joint and degrees of freedom(DOF) to represent the various posture of the hand.

2.1. The skeleton system of a hand

Fig.1 illustrates the hand skeleton system [4]. The hand skeleton consists of the carpus which connected to the wrist, the metacarpus and the phalanges. The carpus consists of 8 carpi. The metacarpus are 5 metacarpalia. The phalanges can be devided to Phalanx proximals, Phalanx media, phalangis. Only the thumb has two phalanges. The carpus have delicate deformation because its 8 elements can slide each other subtly. But we modeled the carpus as a rigid link considering that its effects on the surface deformation was neglectable.

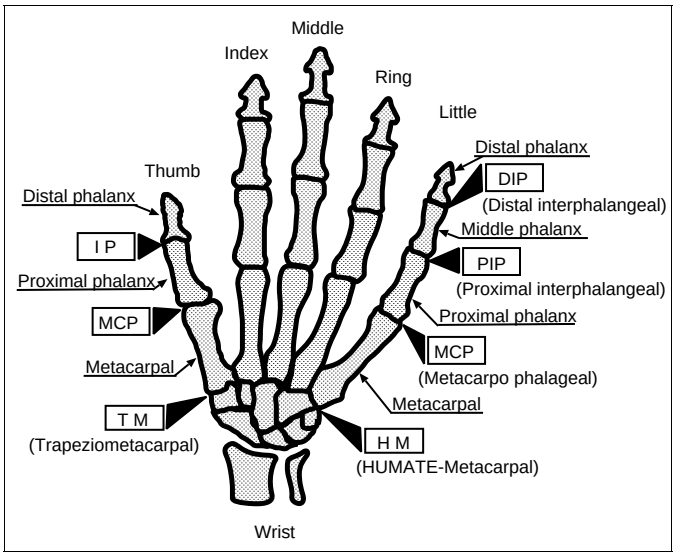

Figure 1. Diagram for the human hand skeleton

2.2. Kinematics

When we represent a posture of the hand, we can utilize the hierarchical sturucture of skeleton system[2]. So we can determind the joints position from wrist to each finger end. In oreder to describe the joints posture, we use the 3D coordinates systems as seen in the Fig. 2.

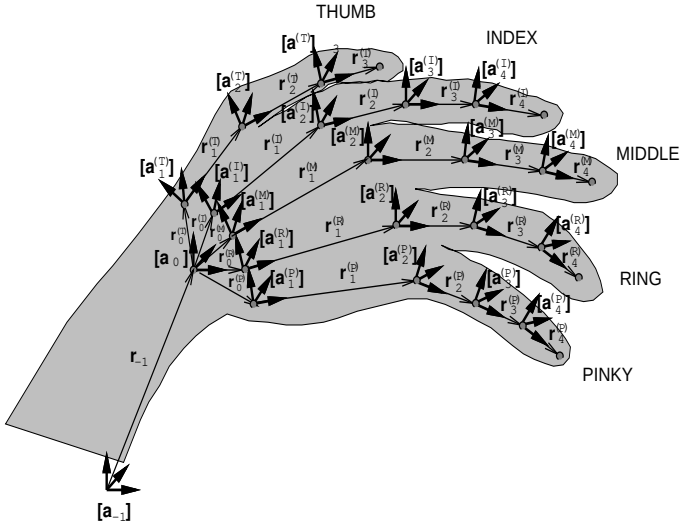

Figure 2. Coodinates systems

2.3. Locul coordinates

First, We settle the world coordinate. We represent each unit bases vector of the world coordinate as $\boldsymbol{a}_{-1,1}$,$\boldsymbol{a}_{-1,2}$, $\boldsymbol{a}_{-1,3}$. So We can express the bases vector system as

$$[\boldsymbol{a}_{-1}]^T = [\boldsymbol{a}_{-1,1} \ \ \boldsymbol{a}_{-1,2} \ \ \boldsymbol{a}_{-1,3} \ ]. \tag{1}$$

The index k of the each finger is represented as T(the Thumb), I(the Index), M(the Middle), R(the Ring), P(the Pinky). We settle a locul coordinate system on each link j of the finger k. The origins of the locul coordinates are on the joints $C_j^{(k)}$. We represent the bases vector system of each link as

$$[\boldsymbol{a}_j^{(k)}]^T = [\boldsymbol{a}_{j1}^{(k)} \ \ \boldsymbol{a}_{j2}^{(k)} \ \ \boldsymbol{a}_{j3}^{(k)} \ ]. \tag{2}$$

We defined the vecter on each link as

- $\boldsymbol{r}_{-1}$: the position of the carpas
- $\boldsymbol{r}_j^{(k)}$: the vector from the joint $C_j^{(k)}$ to the joint $C_{j+1}^{(k)}$.

In order to caliculate the position of the joints, the coodinates are tranceformed by 3-2-1 Euler angular matrices. By this transformation, locul coodinates are rotated around the 3rd axis by the angle θ_3, then around the 2nd axis by the angle θ_2, and around the 1st axis by the angle θ_1. When each transformation matrix expressed as A_1, A_2, A_3, the coodinates tranceformation from the coordinates system $[\boldsymbol{a}_{j-1}]$ to $[\boldsymbol{a}_j]$ is caliculated as

$$[\boldsymbol{a}_j]^T = A_{jj-1}[\boldsymbol{a}_{j-1}]^T. \tag{3}$$

,where,

$$A_{jj-1} = A_1(\theta_{j1})A_2(\theta_{j2})A_3(\theta_{j3}). \tag{4}$$

The tranceformation from locul coordinates to the world coordinates is expressed as

$$A_{j-1}^{(k)} = \prod_{l=0}^{j} A_{ll-1}^{(k)}. \tag{5}$$

The position vector of $C_{(j)}^{(k)}$, the (j)th joint of the finger(k) in the world coodinates is expressed as

$$\boldsymbol{x}_1^{(k)} = \boldsymbol{r}_{-1} + \sum_{j=0}^{3} A_{j-1}^{(T)T} \boldsymbol{r}_j^{(k)} \tag{6}$$
$$(k = T)$$

$$\boldsymbol{x}_1^{(k)} = \boldsymbol{r}_{-1} + \sum_{j=0}^{4} A_{j-1}^{(k)T} \boldsymbol{r}_j^{(k)}. \tag{7}$$
$$(k = I, M, R, P)$$

Table 1. degrees of freedom in the model

	the wrist	TM	MCP	PIP,DIP,IP
number of joints	1	3	5	9
trancelate	3	-	-	-
rotate	3	2	2	1
sum of DOF	6	10	10	9

2.4. The degrees of freedom in each joint

Using the formultation of the kinematics, the whole posture of the skeleton system is determined by giving the position of the wrist and Euler angles as joint angles. The angle between j-th link and $(j-1)$-th link belonging to the finger k is expressed as $\theta^k_{(j)}$, which is used as a state variable of this system. We assume that joint(1) of Thumb and joint(2) of all fingers have two degrees of freedom (rotational components around x and z axis), and the other joints have only one(rotational component around x-axis) (Table[1]).

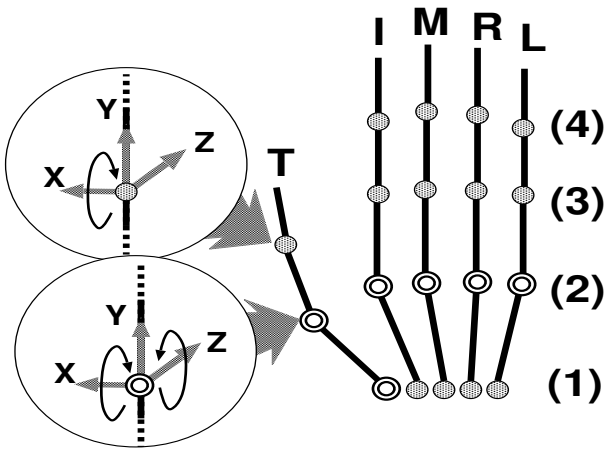

Figure 3. skeleton model

3 Posture determination process

As we all know, each joint in a hand can not move independently. There are some rules that determining the interrelation when bending the fingers. We utilize these characteristics of human hand as constraints in order to generate natural hand motion with few inputs. In this section, we describe the inputs system which can generate the natural finger skeleton posture by create inner inputs automatically when the user gives few inputs to the system. The dynamic model consists of a skeleton model and a inner torque energy. Skeleton model is represented by links with joints and virtual springs, which determine the stiffness of each joint of fingers. Inner torque between joints and fingers are derived from a inner torque energy.

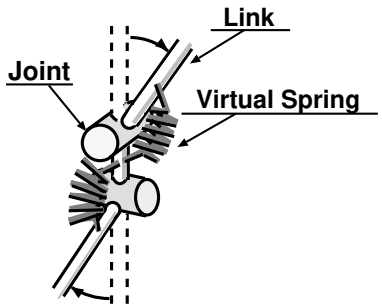

Figure 4. virtual spring

3.1. System equation

We assigned a virtual spring to each degree of freedom of joint(Fig4). State variables are determined by equilibrium between the elastic torque of virtual spring and the input torque. This is expressed as the following equation,

$$K\,\boldsymbol{\theta} \;=\; \boldsymbol{\tau} \qquad (8)$$

$\boldsymbol{\theta}$: state variable vector
$\boldsymbol{\tau}$: input torque vector
K : stiffness matrix

where, the matrix K is diagonal matrix which represents stiffness of the virtual springs.

3.2. Natural posture

We defined the natural posture which the inner inputs should create. Based on the idea that the angles of the fingers don't move independently (Fig.5), we represented the natural posutre by linear combination of the statevalues of the system.

$$\alpha\theta_1 + \beta\theta_2 + \gamma \;=\; 0 \qquad (9)$$
$$\alpha, \beta, \gamma \;:\; const.$$

We considered that the inner inputs were a sort of the central force. So we constructed the potential energy J_1 of inner inputs by the quadratic form as

$$J_1 \;=\; \frac{1}{2}\, w\, (\alpha\theta_1 + \beta\theta_2 + \gamma)^2 \qquad (10)$$
$$(w : elastisity\ parameter)$$

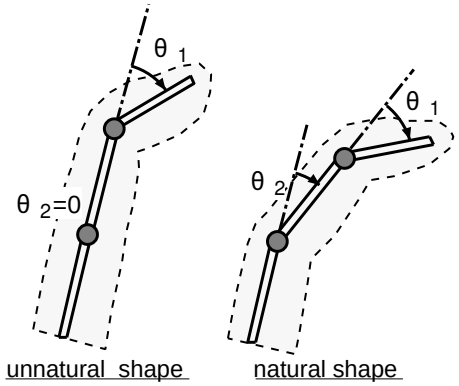

Figure 5. Natural posture

,where $w$is a parameter of elastisity that determine the strength of the inner input. This potential energy J_1 is a function of the joint angles which motioin have the relationship mutually. Then We can construct the potential energy of whole hand by linear summation of the energies of all relationships of joints. The equlibrium of this energy create the natural posture and the inner inputs make the equilibrium state of the hand. The inner inputs tocreate the natural posture is derived by caliculating the partialfraction respect to the statevalues as following.

$$\tau_{c1} = -\left(\frac{\partial J_1}{\partial \theta_1}\right) \quad (11)$$

$$= -w\alpha(\alpha\theta_1 + \beta\theta_2 + \gamma) \quad (12)$$

As we described, natural posture of the hand is defined as the equilibrium state of the dynamic model of the hand. The potential energy J of the input to the dynamic system is defined by the following equation.

$$J = \frac{1}{2}\,\boldsymbol{\Theta}^T W\,\boldsymbol{\Theta} \quad (13)$$

Where, $\boldsymbol{\Theta} = A\boldsymbol{\theta} + \boldsymbol{b}$ is a linear combination of $\boldsymbol{\theta}$, the state variables the component of W express the gains of inner torques. The inner torque vector $\boldsymbol{\tau}_c$ is derived by partial differentiation of energy with respect to the state variable vector as the following.

$$\boldsymbol{\tau}_c = -\left(\frac{\partial J}{\partial \boldsymbol{\theta}}\right) \quad (14)$$

$$= -\left\{\left(\frac{\partial J}{\partial \boldsymbol{\theta}^T}\right) + \left(\frac{\partial J}{\partial \boldsymbol{\theta}}\right)^T\right\}$$

$$= -A^T W(A\boldsymbol{\theta} + \boldsymbol{b}) \quad (15)$$

3.3. Determination of hand posture

We call the user inputs as direct the inputs, and the inputs which keeps natural skeleton posture as inner inputs. Total inputs to the system are the sum of these two inputs and expressed as

$$\boldsymbol{\tau} = \hat{\boldsymbol{\tau}} + \boldsymbol{\tau}_c \quad (16)$$

$\hat{\boldsymbol{\tau}}$: direct input torque vector
$\boldsymbol{\tau}_c$: inner input torque vector

Once the direct inputs are given to some joints, the state of the inner torque energy J is changed because J is a function of $\boldsymbol{\theta}$. In order to get the equilibrium state of a whole hand posture inner torques work has to be obtained for each joint. So the direct input torque vector can be sparce one, that is there is no need to give as large number of inputs as the degrees of freedom of a whole hand.

State variable vector $\boldsymbol{\theta}$ in a equilibrium state is determined by the following equations.

$$\begin{cases} K\,\boldsymbol{\theta} = \boldsymbol{\tau} \\ \boldsymbol{\tau} = \hat{\boldsymbol{\tau}} + \boldsymbol{\tau}_c \end{cases} \quad (17)$$

$$K\,\boldsymbol{\theta} = \hat{\boldsymbol{\tau}} + \boldsymbol{\tau}_c$$

$$= \hat{\boldsymbol{\tau}} - A^{\mathrm{T}} W(A\,\boldsymbol{\theta} + \boldsymbol{b})$$

$$(K + A^{\mathrm{T}} W A)\,\boldsymbol{\theta} = \hat{\boldsymbol{\tau}} - A^{\mathrm{T}} W\boldsymbol{b} \quad (18)$$

3.4. Determination of energy parameters

In order to determine the parameters in the potential energy of the inner inputs, we sampled fo real finger motions. The measureing of the finger motions is a difficult work. So we chose the joints that may have some relationship in their motions and the camera conditions so that the observed motion can be considerd as 2 dimensional. Using a digital video camera, we took 10 to 30 pictures of finger joints while one cycle of flex and extention.

Then we plotted the motiondata on the state variable plane and got the approximated linear function and the dispersion around the linear function (Fig.6). We uesd the function as the natural posture and constructed the A matrix. We determined the weight parameter of constraints which is the elemens of the matrics W based on the normarized values of the dispersion around the function.

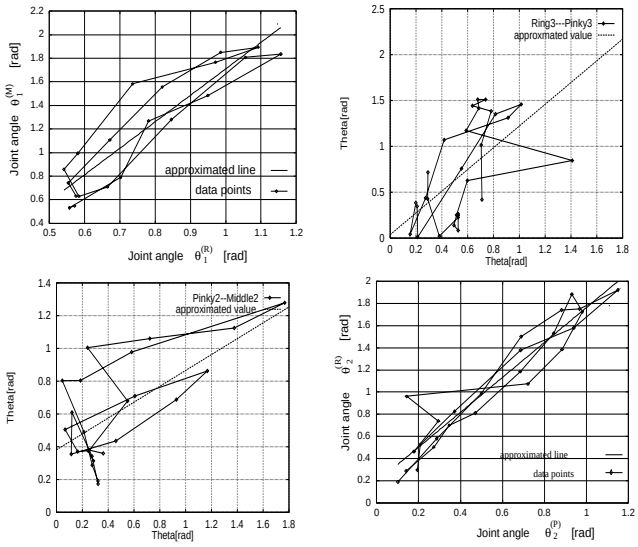

Figure 6. Examples of sampled finger motion data (left)the index and middle finger PIP,DIP relationshipthe index and ...

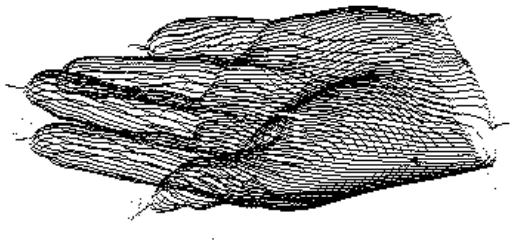

Figure 7. range data

4. Surface generation

The 3D hand surface model is generated by a graphics workstation. At first, we obtained 3D range data of a whole hand using raser range-finder. In order to express the hand surface which must be deformable according to the motion of the hand skeleton, we made a data construction specialized to human hand. Each 3D data of point on the surface have not only adjacent points information but attribution to a link of skeleton model(9).

4.1. Range data

We measured the 3D shape of a replica of a hand which is made of plaster. We used a plane scan range-finder and obtained shape data set of the palm and the back side. We attached 9 markers of projections to the replica before measuring. We adjusted the 3D positions of two data sets besed on the position of the markers included in the both of the data set by caliculating the quadratic error minimizing. So we could get range data of almost a whole hand(Fig.7).

4.2. Data construction

There need to make right relationship between the range data and the skelton model in order to make deformatioin accrding to the motion of the skeleton model. So each data of measured point should has also the information which link of the skeleton model the point is affected. We settled the position the skeleton model in the world coordinate whidh is the same of that palm side meadsuering.

Two sets of range data had defferent coordinates when they measured. The range data of a whole hand is made by tranceformation of the back side data to the coordnate of palm side. So the scanning lines of palm and back side are belong to two defferent coordinates. We took the procedure as following8.

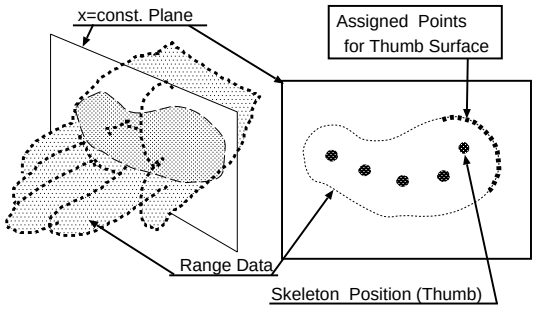

Figure 8. Procedure to get the poligon verteces

1. Settling the 50 section planes ($x = const.$plane in the world coordinate)
2. Projection the suffiiciently near points on to each section plane
3. Grouping the points by detection of the nearest link from each point on the section planes.
4. Generating the poligon vertices row of 10 points within the same link groupe on each section planes by linear interpolation

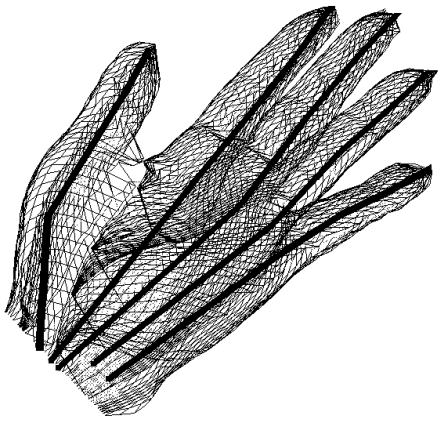

Figure 9. wire framed model

4.3. Deformation of the surface model

Now we have got a poligonal surfaces which have the attribution to the skeleton links. When a skeleton link move, the surface of the link can move together. Each link surface moves link a rigid object according to the motion of the skeleton posture, rotating around the joints. So that the sufaces around joints always continuous even when the fingers move the edge lines are shared by the neiboring link surfaces. The whole hand surface could be represented like a continuous skin.

5. Experiment

In order to evaluate the effectiveness of the proposed hand model. We built a simple GUI(Graphic User Interface) to allow a user to assign the desired angles of the joints, and a model renderer to generate the hand images as well as the hand model itself. At first, we input the sequence of the angles of the joints we want to move. The angles of the joints that we did not give are determined by the dynamic model. After that hand surface is generated with the surface model based on determined the angle of the joints, which is then sent to model renderer to generate the hand animation. The system is implemented on a SGI $Indigo^2$ workstation.

The hand surface is composed of about 8000 triangle meshes (Fig.10). Fig.?? illustrates a sample of generated hand motion animation. The posture of the state without inputs is shown in the upper frame. Two middle and bottom frame shows followed motion of the generated hand animation, where we only assigned the angles of the joints of the thumb and the middle finger. The animation of the motion of the fingers on the spot, using our GUI.

6. Discussion

As seen in (Fig.10) and (Fig.??), we could get sufficient realty in terms of the shape and the motion. The model can be used as a agent in the virtual realty(VR) environment , indicating or touching or grasping something and so on, as well as creating hand animation. We conseder that the posture determination process can be applied to biomedical engineering deeling with prosthetics. It is extremely useful that utilizing the limited inputs to control a object like an artifitial hand for disabled people.

7. Conclusions

We introduced dynamics to a human hand model by using virtual springs and a inner torque energy in a skeleton model. We also built a surface model of hand based on 3D shape measurement data and photorealistic hand can be synthesized with the model. The natural posture of a hand is defined as the equilibrium state of the dynamic model, which can express the complicated effects of the interference between finger motions. The desired natural posture of the hand can be generated by only assigning a few key angles of the joints. The experiment showed that the hand animation can be designed easily and the generated hand animation is natural and smooth.

References

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Figure 10. Poligon surface

Figure 11. Motion sequece