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著者	Takeuchi Hiroki, Watanabe Tetsuyou
journal or publication title	Proceedings of the International Symposium on Robotics (ISR)
number	2010
page range	606-612
year	2010-01-01
URL	http://hdl.handle.net/2297/35246

Development of a Multi-fingered Robot Hand with Softness-changeable Skin Mechanism

Hiroki Takeuchi[1] and Tetsuyou Watanabe[1]
1 Graduate School of Natural Science & Technology, Kanazawa University, Kakuma-machi, Kanazawa-shi, 920-1192, JAPAN

This paper develops a multi-fingered robot hand with skin mechanism enabling softness change. We show how the softness of the skin affects grasping and manipulation. Elastic skin provides stable grasping while precise manipulation is lost. Hard skin provides precise manipulation while stability of grasp is lost. We will try to change the softness of the skin according to situation, object, and so on. In this paper, we develop a novel human like robot hand with softness-changeable skin mechanism.

1 Introduction

Recently there are many attentions to develop a robot which can work in human society. One of the most important functions is to (grasp and) manipulate/move an object. Without the function, the robot can not work and help human. Robot hand is one of the devices which have possibility to equip such a function. Our vision of this study is to develop such a robot hand which can work inside human society.

In a daily life, there are many kinds of tools which human being uses. Therefore, Robot hand which resembles human hand is considered to have advantage to work in human society.

Next, for the dexterity, it is also important that thumb opposes the other finger. Without this function, the angle between the tip surface normals for thumb and for the other finger becomes large. Then, robot hand needs large frictional forces to keep grasping.

From the other viewpoint, human lives in an environment which is variously changeable. Therefore, robot hand is required to grasp and manipulate many kinds of unknown objects in the environment. Then, to have dexterity is a key issue for such a robot hand [1] [2] [3] [4] [5] [6]. To improve the dexterity of robot hand, we consider to add a special function which human hand does not have. It is softness changeable skin. Recently, some robot hands have soft surface of the hands like human hand [7]. As with human skin, moderate softness is considered to be advantages to grasp and manipulate objects [8]. Soft skin increases contact area between hand and object and increase frictional force. Since we grasp and manipulate an object through friction, frictional force is essential. However, finger with soft skin sometimes disturbs precise manipulation. Softness might absorb the motion. For example, if moving the fingertip with soft skin which contacts with the object, whole fingertip motion is not directly transmitted to object motion.On the other side, hard skin can transmit. Summarizing, softness and hardness of skin have both advantage and disadvantage. Therefore, skin whose softness/stiffness is changeable has large advantage to improve the dexterity.

Concerning the above, we develop a robot hand named Kanazawa Hand which has following characters.

(1) The shape of the hand resembles human hand.
(2) Thumb opposes every other finger.
(3) Softness-changeable mechanism is attached to skin.

This Kanazawa Hand can attain not only dexterous manipulation with hard skin, but also stable grasping with soft skin, and then appropriately adjust many kinds of situations, objects, and environment.

This paper is organized as follows. First, design of the hand is described. Then the effect of the skin softness on stable grasping and precise manipulation is described, and proposed softness changeable mechanism.

2 Skeletal structure

In this chapter we present the brief structure of the Kanazawa Hand and describe the detail mechanism of its finger module.

2.1 Structure of the hand

Figure 1 shows an overview of the developed hand which has four fingers: thumb, index, middle, and ring fingers. As shown in **Figure 2**, we chose the kinematic structure like human hand so that the robot hand can use many kinds of tools for humans. **Table 1** shows the basic design specification for the hand.

The thumb has 4 DOF for 3 joints: 2 DOF for CM joint, 1 DOF for MP joint, and 1 DOF for IP joint. The CM joint is located at the center with respect to the width direction of the hand (See **Figure 3(a)**). There is rotation axis at the CM joint to be able to twist the thumb (See **Figure 3(b)**). The normal direction of the surface for the thumb finger tip can coincide with that for the other finger tips as shown in **Figure 4(a)**. In contrast, human cannot always make such postures as shown in **Figure 4(b)**. Then, it can be said that the developed thumb has much better mechanism than human from the viewpoint of opposability (thumb ability to oppose the other fingers.)

The index finger has 3 DOF for 3 joints: 2 DOF for MP joint and 1 DOF for PIP joint. DIP joint is coupled with the PIP joint like a human finger. The MP joint with 2 DOF

works to adduct/abduct and flex/extend. This kinematic structure of 3 DOF is completely the same as human index finger.
The mechanism of the middle finger is the same as that of the index finger except for the MP joint mechanism. The middle finger lacks one DOF (adduction/abduction of the MP joint) compared to the index finger. The posture resulted from the adduction/abduction of the MP joint can also be formed by the other finger motion (without the adduction/abduction of the MP joint). Therefore the hand can dexterously manipulate objects even if the one DOF is omitted. That leads advantages of the reduction in size, weight, and the cost of the robot hand.
The ring finger is the same finger structure as the index finger.

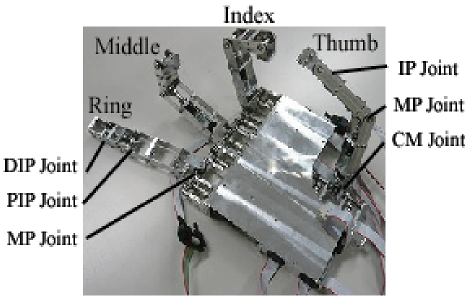


Figure 1 Overview of the Kanazawa hand

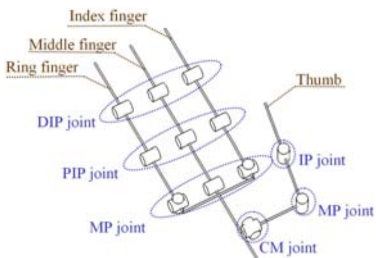


Figure 2 Joint structure

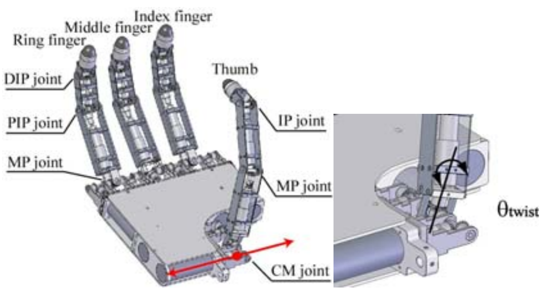


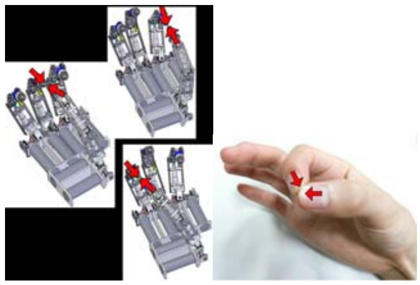
Figure 3 (a)Position of CM joint (b)Twisting mechanism

2.2 Mechanism of a finger module

The hand can be separated into every finger module because the four fingers are mechanically identical. Since each finger module uses almost the same mechanism, we present the only mechanism of the index finger. A finger module has 3 joints (MP, PIP, and DIP) and 3 links (proximal, middle, and distal link) as defined in **Figure 5**. It has 3 DOF: 2 DOF for the MP joint and 1 DOF for the

Table 1 Specification of the Kanazaawa hand

Dimensions	hand	Length	290	[mm]
		Width	160	[mm]
	finger	Length	170	[mm]
		Width	25	[mm]
Fingers			4	[fingers]
Joints		Total	12	[joints]
		Thumb	3	[joints]
		Index	3	[joints]
		Middle	3	[joints]
		Ring	3	[joints]
D.O.F.		Total	12	[D.O.F.]
		Thumb	4	[D.O.F.]
		Index	3	[D.O.F.]
		Middle	2	[D.O.F.]
		Ring	3	[D.O.F.]
Weight			1.5	[kg]
Fingertip force			7	[N]



(a)The Kanazawa Hand (b)Human hand
Figure 4 Thumb opposes the other fingers

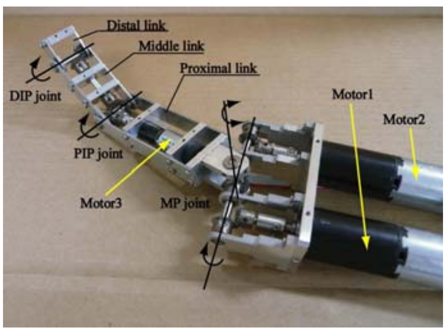


Figure 5 Finger module without finger tip

PIP joint. The DIP joint is coupled with the PIP joint. Two motors (motor 1 and 2) for driving the MP joint are placed in the palm, and one motor (motor 3) for driving the PIP joint is placed in the proximal link. The motor 1 and 2 are DC motors (3.5[W], provided by Maxon motor) with epicyclic gear (gear-ratio 128:1) and encoder (256 pulse/rev). In contrast compact DC motor of motor 3 (0.5[W], provided by Maxon motor) with epicyclic gear (gear-ratio 256:1) and encoder (16 pulse/rev) is used for the PIP joint.
This finger module has two core mechanisms: first one is MP joint mechanism providing two rotations whose axes are orthogonal to each other, second one is DIP-PIP joint mechanism where the DIP and the PIP joints move together. We descried their detail in the following subsections.

2.2.1 MP joint mechanism

The MP joint with 2 DOF works to adduct/abduct and flex/extend. **Figure 6** shows the mechanism of the MP joint in detail. Gears 1 to 4 consist of differential bevel gears mechanism. The gears 1 and 2, driven by the motor 1 and 2 respectively, rotate only about flexion/extension axis. The gear3 is fixed to the proximal link so that the proximal link can adduct/abduct by the gear3. The gear4 is connected to the proximal link and freely rotates in adducent/abducent directon, irrespective of the proximal link motion (rotation). The adduction/abduction axis $\theta_{ad\text{-}ab}$ and the flexion/extension axis $\theta_{fl\text{-}ex}$ are given by:

$$\begin{bmatrix} \theta_{fl-ex} \\ \theta_{ad-ab} \end{bmatrix} = \begin{bmatrix} 1/2 & 1/2 \\ 1/2 & -1/2 \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix} \qquad (1)$$

where θ_1 and θ_2 are the angles driven by the motor 1 and 2.

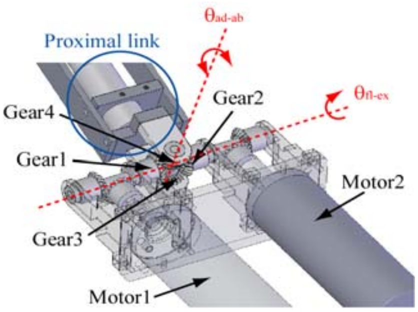


Figure 6 Mechanism of MP joint

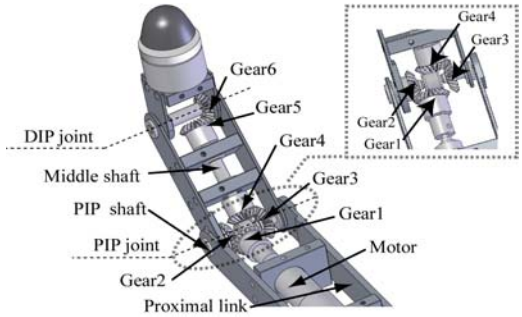


Figure 7 Mechanism of PIP and DIP joint

2.2.2 PIP-DIP joint mechanism

Figure 7 shows the mechanism that the PIP joint is coupled with the DIP joint. To couple the PIP joint with the DIP joint, the specially designed shaft mechanism is developed. **Figure 8** shows the mechanism of the PIP shaft. The PIP shaft consists of two short shaft, a hollow shaft, and two bearings. The shaft 1 drives with the PIP joint by driving the motor, but the shaft 2 does not directly drives with the motor. If the gear 2 connected to the shaft 1 is driven by the motor through the gear 1, PIP joint rotates. Then, the shaft 2 and the gear 3 connected to the shaft are driven, and then the gear 4 rotates about the middle shaft. The rotation of the gear 4 drives the DIP joint through the middle shaft, the gear 5 and the gear 6. Since the gear 1 to 6 are the same gear ratio, the PIP and the DIP joint flex/extend with the same angle.

3 Skin mechanism

Here, we describe softness-changeable mechanism. First, we present why softness-changeable mechanism is needed for grasping and manipulation of the object. Second, we present the novel softness changeable skin mechanism. Lastly, we present fundamental experimental results to show the effectiveness.

3.1 Effect of softness on grasping and manipulation

3.1.1 Frictional effect

Figure 9 shows that a hand grasps a rigid object when using soft contact area and hard contact area. We define stable grasping as a hand being able to continue to hold an object even when gravity or external force is exerted on the object. To balance large external forces, we need large contact forces. Since contact forces are constructed by

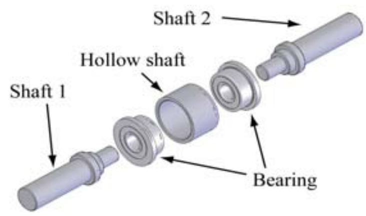
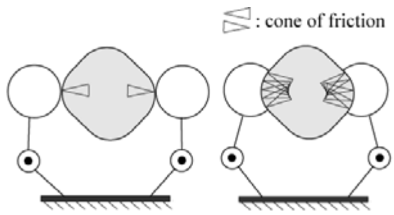


Figure 8 Design of PIP shaft



(a) Hard skin (b) Soft skin

Figure 9 Grasping an object with hard skin and soft skin normal force and frictional (tangent) forces, friction has an important role to enlarge contact forces. To increase contact force, there are two methods: one is to increase normal force, the other is to increase friction. However, it is not practical to increase normal force. Frictional forces increase with the increase of normal force. However, its increasing amount is low if friction is small. Then, we can increase contact forces in only limited directions. Additionally, large force per unit area, namely, large pleasure might cause destruction of a fragile object. Therefore, large friction is important for stable grasping. If considering the softness of skin, soft skin provides large contact area comparing with hard skin. In case of using soft skin, the contact area can deform its shape along the shape of the object shown in Figure 9. It means we can get larger contact area, and then can get larger friction forces without changing the magnitude of normal force. Hence it can be said that finger with soft contact area is superior to finger with hard contact area for stable grasping.

3.1.2 Quasi-static analysis from the viewpoint of manipulability

Here, we discuss manipulability [9] to understand how easily the hand can manipulate the object. **Figure 10** shows the model of the fingertip and the object. For the convenient, we discuss only fingertip motion, and assume that we can move the fingertip in arbitrary directions. Every fingertip has a shape of deformable hemisphere. The object has flat surface at the contact point and is rigid body. We consider to grasp the object with n fingertips. Let Σ_o and Σ_i be the coordinates located at the gravity center of the object and at the center of hemisphere of ith fingertip. Let be $\boldsymbol{p}_i$ and $\boldsymbol{p}_o$ are the positions of the origin of Σ_o and Σ_i, and $\boldsymbol{p}_{ci}$ be the position of the center of the contact surface between the fingertip and the object. $\boldsymbol{\omega}_i$ and $\boldsymbol{\omega}_o$ are angular velocities of Σ_o and Σ_i. $\boldsymbol{n}_i$ is unit contact normal directing inside of the object. $\boldsymbol{t}_{1i}$ and $\boldsymbol{t}_{2i}$ are unit contact tangential vectors. r_i is the hemisphere radius of the fingertip and Δr_i is the deformation amount by contact. Δr_i can be a parameter expressing skin softness. If Δr_i is large, it means the skin is soft and vice versa.

The relationship between $\boldsymbol{p}_{ci}$ and $\boldsymbol{p}_i$ is given by

$$\boldsymbol{p}_{ci} = \boldsymbol{p}_i + (r_i - \Delta r_i)\boldsymbol{n}_i \quad (2)$$

If differentiating this relationship with respect to time, we get

$$\dot{\boldsymbol{p}}_{ci} = \dot{\boldsymbol{p}}_i + (r_i - \Delta r_i)(\boldsymbol{\omega}_i \times \boldsymbol{n}_i + \boldsymbol{v}_i) - \Delta \dot{r}_i \boldsymbol{n}_i \quad (3)$$

where

$$\boldsymbol{v}_i = \boldsymbol{R}_i {}^i\dot{\boldsymbol{n}}_i \quad (4)$$

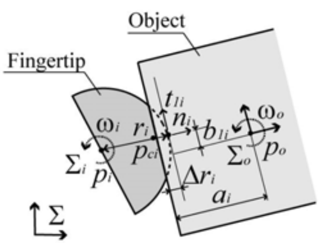


Figure 10 Model of the fingertip and the object

where $\boldsymbol{R}_i$ denotes rotational matrix of Σ_i.

On the other side, the relationship between $\boldsymbol{p}_{ci}$ and $\boldsymbol{p}_o$ is given by

$$\boldsymbol{p}_{ci} = \boldsymbol{p}_o + a_i \boldsymbol{n}_i + b_{1i}\boldsymbol{t}_{1i} + b_{2i}\boldsymbol{t}_{2i} \quad (5)$$

where a_i, b_{1i} and b_{2i} denote the distances between Σ_o and $\boldsymbol{p}_{ci}$ along the directions of $\boldsymbol{n}_i$, $\boldsymbol{t}_{1i}$ and $\boldsymbol{t}_{2i}$, respectively. Note that a_i is constant since it represents the distance between Σ_o and the side of the object.

If differentiating this relationship with respect to time, we get

$$\begin{aligned}\dot{\boldsymbol{p}}_{ci} = \dot{\boldsymbol{p}}_o + \boldsymbol{\omega}_o \times (a_i \boldsymbol{n}_i + b_{1i}\boldsymbol{t}_{1i} + b_{2i}\boldsymbol{t}_{2i}) \\ + \dot{a}_i \boldsymbol{n}_i + \dot{b}_{1i}\boldsymbol{t}_{1i} + \dot{b}_{2i}\boldsymbol{t}_{2i}\end{aligned} \quad (6)$$

From eq.(3) and (6), the following equation is obtained.

$$\begin{aligned}\dot{\boldsymbol{p}}_i + (r_i - \Delta r_i)(\boldsymbol{\omega}_i \times \boldsymbol{n}_i) - \Delta \dot{r}_i \boldsymbol{n}_i \\ = \dot{\boldsymbol{p}}_o + \boldsymbol{\omega}_o \times (a_i \boldsymbol{n}_i + b_{1i}\boldsymbol{t}_{1i} + b_{2i}\boldsymbol{t}_{2i})\end{aligned} \quad (7)$$

Here we use the following relationships: $\dot{a} = 0$ and

$\dot{b}_{1i}\boldsymbol{t}_{1i} + \dot{b}_{2i}\boldsymbol{t}_{2i} = (r_i - \Delta r_i)\boldsymbol{v}_i$

which expresses there is no slippage between the fingertip and the object. Eq.(7) can be rewritten by

$$\boldsymbol{G}_{fi}{}^T \begin{bmatrix} \dot{\boldsymbol{P}}_i \\ \boldsymbol{\omega}_i \end{bmatrix} = \boldsymbol{n}_i \Delta \dot{r}_i + \boldsymbol{G}_{oi}{}^T \begin{bmatrix} \dot{\boldsymbol{P}}_o \\ \boldsymbol{\omega}_o \end{bmatrix} \quad (8)$$

where

$$\begin{aligned}\boldsymbol{G}_{fri}{}^T &= \begin{bmatrix} \boldsymbol{I}_3 & -r_i[\boldsymbol{n}_i \times] \end{bmatrix} \\ \boldsymbol{G}_{oi}{}^T &= \begin{bmatrix} \boldsymbol{I}_3 & -[(a_i \boldsymbol{n}_i + b_{1i}\boldsymbol{t}_{1i} + b_{2i}\boldsymbol{t}_{2i})\times] \end{bmatrix} \\ \boldsymbol{G}_{fdi}{}^T &= \begin{bmatrix} \boldsymbol{O}_3 & [\boldsymbol{n}_i \times] \end{bmatrix} \\ \boldsymbol{G}_{fi}{}^T &= \boldsymbol{G}_{fri}{}^T + \Delta r_i \boldsymbol{G}_{fdi}{}^T\end{aligned} \quad (9)$$

If aggregating Eq.(8) for all n contact points, we get

$$\boldsymbol{G}_f{}^T \dot{\boldsymbol{x}}_f = \boldsymbol{N} \Delta \dot{\boldsymbol{r}} + \boldsymbol{G}_o{}^T \dot{\boldsymbol{x}}_o \quad (10)$$

where

$$\dot{\boldsymbol{x}}_i = \begin{bmatrix} \dot{\boldsymbol{p}}_i \\ \boldsymbol{\omega}_i \end{bmatrix}, \quad \dot{\boldsymbol{x}}_o = \begin{bmatrix} \dot{\boldsymbol{p}}_o \\ \boldsymbol{\omega}_o \end{bmatrix}, \quad \dot{\boldsymbol{x}}_f = \begin{bmatrix} \dot{\boldsymbol{x}}_1 \\ \dot{\boldsymbol{x}}_2 \\ \vdots \\ \dot{\boldsymbol{x}}_n \end{bmatrix}$$

$$\boldsymbol{G}_f{}^T = \begin{bmatrix} \boldsymbol{G}_{f1}{}^T & & \boldsymbol{0} \\ & \boldsymbol{G}_{f2}{}^T & \\ & & \ddots & \\ \boldsymbol{0} & & & \boldsymbol{G}_{fn}{}^T \end{bmatrix}$$

$$\boldsymbol{N} = \begin{bmatrix} \boldsymbol{n}_1 & & \boldsymbol{0} \\ & \boldsymbol{n}_2 & \\ & & \ddots & \\ \boldsymbol{0} & & & \boldsymbol{n}_n \end{bmatrix}$$

$$\boldsymbol{G}_o{}^T = \begin{bmatrix} \boldsymbol{G}_{o1}{}^T \\ \boldsymbol{G}_{o2}{}^T \\ \vdots \\ \boldsymbol{G}_{on}{}^T \end{bmatrix}$$

Here we consider the generable object velocity with the contact velocity whose magnitude is equal to or less than 1. The set of the generable object velocity is expressed by

$$| \boldsymbol{N} \Delta \dot{\boldsymbol{r}} + \boldsymbol{G}_o{}^T \dot{\boldsymbol{x}}_o | \le 1 \quad (11)$$

This means that the magnitude of generable object velocity decreases with the icrease of the deformation velocity $\Delta\dot{r}$. It means deformation might decrease manipulability (how easily we can generate object velocity $\dot{x}_o$).

Now, we discuss the case when $\Delta\dot{r} \to 0$ to simplify the analysis. In this case, Eq.(10) becomes

$$G_f^T \dot{x}_f = G_o^T \dot{x}_o = \dot{p}_c \quad (12)$$

Since $G_o^T \dot{x}_o$ does not include any parameters related with the deformation, there is no effect of the deformation about how much large object velocity can be generated with contact velocity whose magnitude is equal to or less than 1. Then, we consider how much large contact velocity we can generate with the fingertip velociy whose magnitude is equal to or less than 1. It direcly coressponds to how much large object velocity we can generate with the fingertip velociy whose magnitude is equal to or less than 1. From eq.(12), we get

$$\dot{x}_f = \left(G_f^T\right)^+ \dot{p}_c + \left(I - G_f G_f^+\right)k \quad (13)$$

where $\left(G_f^T\right)^+$ denotes the psedo-inverse matrix of G_f^T and k denotes an arbitrary vector. Then, we obtain

$$\begin{aligned} 1 &\geq \dot{x}_f^T \dot{x}_f \\ &= \dot{p}_c^T G_f^+ \left(G_f^T\right)^+ \dot{p}_c + k^T \left(I - G_f G_f^+\right)^2 k \\ &\geq \dot{p}_c^T G_f^+ \left(G_f^T\right)^+ \dot{p}_c = \dot{p}_c^T (G_f^T G_f)^+ \dot{p}_c \\ &= \dot{p}_c^T (\mathrm{diag}\left(G_{fi}^T G_{fi}\right))^+ \dot{p}_c \end{aligned} \quad (14)$$

where diag denotes block diagonal matrix constructed by the following elements. This set expresses the set of generable contact velocity with the fingertip velocity whose magnitude is equal to or less than 1. Then, the magnitude of the generable contact velocity depends on $(\mathrm{diag}\left(G_{fi}^T G_{fi}\right))^+$, namely $G_{fi}^T G_{fi}$. The larger $G_{fi}^T G_{fi}$ is, The larger $\dot{p}_c$ we can generate.

From eq.(14), we get

$$G_{fi}^T G_{fi} = G_{fri}^T G_{fri} + \Delta r_i \left(G_{fdi}^T G_{fri} + G_{fri}^T G_{fdi}\right) + \Delta r_i^2 G_{fdi}^T G_{fdi} \quad (15)$$

Here, we define the following two matrices expressing the term which does not include the Δr_i and the term including Δr_i, resectively.

$$\begin{aligned} G_{fi}^T G_{fi} &= G_{1i} + G_{2i} \\ G_{1i} &= G_{fri}^T G_{fri} \\ G_{2i} &= \Delta r_i \left(G_{fdi}^T G_{fri} + G_{fri}^T G_{fdi}\right) + \Delta r_i^2 G_{fdi}^T G_{fdi} \end{aligned} \quad (16)$$

From eq.(16), G_{2i} is expressed by

$$G_{2i} = (\Delta r_i^2 - 2 r_i \Delta r_i) G_{fdi}^T G_{fdi} \preceq 0 \quad (17)$$

because $\Delta r_i \leq r_i$. Here $0 \preceq A$ means the matrix A is semi-denfinite. From this relationship and eq.(16), we can get the following relationship

$$G_{1i} + G_{2i} \preceq G_{1i} \quad (18)$$

This means the magnitude of generable contact velocity decreases with the icrease of deformation Δr. Namely, the magnitude of generable object velocity decreases with the icrease of deformation Δr.

3.1.3 Dynamical analysis

Here, we discuss softness effects from the viewpoint of dynamics. In order to consider dynamic behavior of the deformation, we utilize a four-element viscoelastic model: two springs and two dampers (See **Figure 11**). This model can express both hard skin and soft skin. If spring constant k and viscosity coefficient c are large, it means hard skin. In contrast, soft skin can be expressed by small spring constant k and viscosity coefficient c. For the convenient, we consider only fingertip motion. Let be f_{ri} the force exerted on the contact surface of the fingertip in the normal direction. Then, relationship between f_{ri} and Δr_i is given by

$$\begin{aligned} \Delta r_i &= \Delta r_{i1} + \Delta r_{i2} + \Delta r_{i3} \\ k_{i1} \Delta r_{i1} &= f_{ri} \\ k_{i2} \Delta r_{i2} + c_{i2} \Delta \dot{r}_{i2} &= f_{ri} \\ c_{i3} \Delta \dot{r}_{i3} &= f_{ri} \end{aligned} \quad (19)$$

From eq.(10) and the principle of virtual work, we get

$$\begin{aligned} w_{fi} &= G_{fi} f \\ f_r &= N^T f \\ w_o &= G_o f \end{aligned} \quad (20)$$

where f is contact force vector, w_{fi} is the force and moment corresponding to the contact force f, and w_o is the resultant force and moment applied to the object.

The motion equation of the ith fingertip and the object are respectively given by

$$M_i \ddot{x}_i + (\frac{1}{2}\dot{M}_i + S_i)\dot{x}_i + w_{fi} = u_i \quad (21\text{-a})$$

$$M_o \ddot{x}_o + (\frac{1}{2}\dot{M}_o + S_o)\dot{x}_o = w_o \quad (21\text{-b})$$

where M_i and M_o are inertia matrixes of ith fingertip and the object, S_i and S_o are the skew-symmetric matrixes to express nonlinear forces such as Coriolis forces for ith fingertip and the object, and u_i is the input force and moment vector for the fingertip.

Here, we consider the following input force (and moment) U and output velocity $\dot{\Lambda}$:

$$U = \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_n \\ w_o \end{bmatrix}, \quad \dot{\Lambda} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \vdots \\ \dot{x}_n \\ \dot{x}_o \end{bmatrix}$$

The sum of kinetic energies for the fingertip and the object is represented by

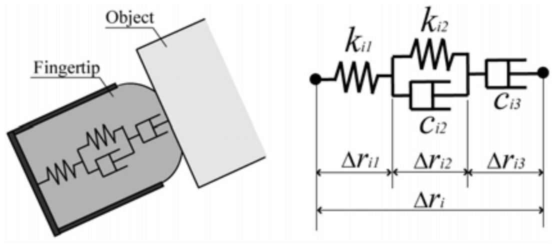


Figure 11 Model of contact deformable area

$$K = K_f + K_o = \sum_i \frac{1}{2} \dot{\boldsymbol{x}}_i^T \boldsymbol{M}_i \dot{\boldsymbol{x}}_i + \frac{1}{2} \dot{\boldsymbol{x}}_o^T \boldsymbol{M}_o \dot{\boldsymbol{x}}_o \tag{22}$$

The potential energy of the deformation part is expressed by

$$E_p = \sum_i \sum_{j=1}^{2} k_{ij} \Delta r_{ij}^2 \tag{23}$$

Then, from eq.(19) to eq.(23) , the total power is represented by

$$\boldsymbol{U}^T \dot{\boldsymbol{\Lambda}} = \frac{dK_f}{dt} + \sum_i \boldsymbol{w}_{fi}^T \dot{\boldsymbol{x}}_i = \frac{d(K + E_p)}{dt} + \sum_i \sum_{j=2}^{3} c_{ij} \Delta \dot{r}_{ij}^2 \tag{24}$$

Here, we consider the case when the input is zero. Then, eq.(24) becomes

$$\frac{d(K + E_P)}{dt} = -\sum_i \sum_{j=2}^{3} c_{ij} \Delta \dot{r}_{ij}^2 \tag{25}$$

From this relationship, it can be said that even if the input is zero, the system will approach to its equilibrium state if the skin is soft and corresponding c_{ij} is large. On the other side, if the skin is hard and corresponding c_{ij} is small, it is hard to expect that the system will converge, and kinetic and potential energies tend to preserve. Therefore, we can get more stability with soft skin. From the viewpoint of convergence to the desired position, we need to use control law to compensate the potential energies. If the skin is soft, the corresponding potential energies are large and vice versa. Then, we can easily control the system with hard skin and can not with soft skin. Summarizing, hard skin has advantage for manipulation and disadvantage for grasping while soft skin has advantage for grasping and disadvantage for manipulation.

3.2 Mechanism to change softness of skin

Figure 12 shows the structure of softness-changeable mechanism for a fingertip. We developed the fundamental structure shown by gray colour. Its shape is crosswisely cut circular cylinder, and it is made of duralumin. We fit a peltier device in the inside of its side surface, and fill agar impression material in the cylinder. The end of fingertip is covered with elasticized rubber made from latex. Agar impression material is a special material which can turn soft by heating and hard by cooling, and has reversibility. On the other hand, the temperature of peltier device can be controlled by electric current. Then, this skin can turn soft and hard by controlling electric current.

Figure 13 shows the relationship between the intensity of the electric current for the peltier device and the elastic modulus of the skin mechanism. It can be seen that the elastic modulus of the skin mechanism changes from 1.5[kPa] to 20[kPa] by controlling the electric current from 1.4 [A] to 1.8[A]. The range of the changeable elastic modulus is considered to be enough large.

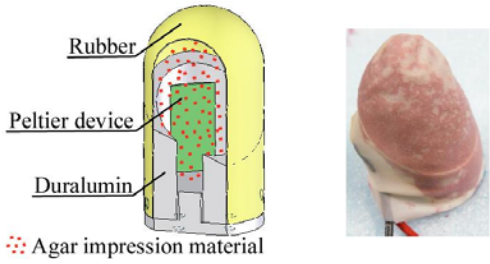


Figure 12 Structure of softness changiable skin

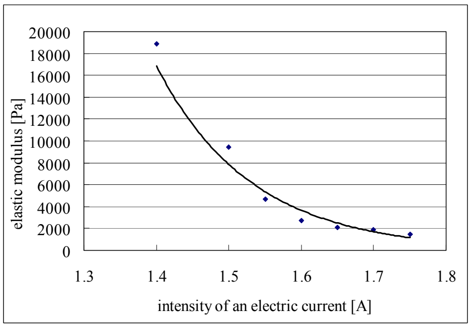


Figure 13 Relation between intensity of an electric current for peltier device and elastic modulus of skin mechanism

3.3 Fundamental experiment

In order to see the effectiveness of our developed system, we conducted the experiment how an object reacts during manipulation. **Figure 14** shows the overview of the experiment. The object is rigid, circular flat plate in shape, and 0.3[kg]. It is pinched by two fingertips disposed antipodally. The horizontal line on the object and red triangular marker on the fingertips is in the same straight line at the start. Now, we try to observe the positional relationship between the horizontal line and the marker after rotating the object with 45 degrees by moving the two fingertips.

Figure 15 shows the experimental results when the hard skin with elastic modulus of 15[kPa] is used and the soft skin with elastic modulus of 2[kPa] is used. Note that the elastic modulus for hard skin is over the range shown in Figure 13 due to the variation of the used Agar impression material. In case when using the hard fingertip shown in Figure 15(a), the line on the object and the two red markers could keep to be on the same line during the manipulation. On the other side, when using soft skin shown in Figure 15(b), they could not. If the fingertip moves, the object rotates with a little delay. The delay causes the declination (the line on the object and the two red markers are not on the same line). Therefore, in order to complete the 45 degree rotation with soft skin, we need to move the fingertips more comparing to the case when using hard skin. Then, it can be said that the finger with hard skin has advantage for manipulation comparing to soft skin.

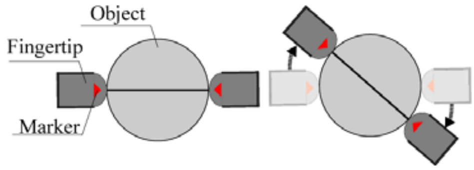


Figure 14 Overview of the experiment

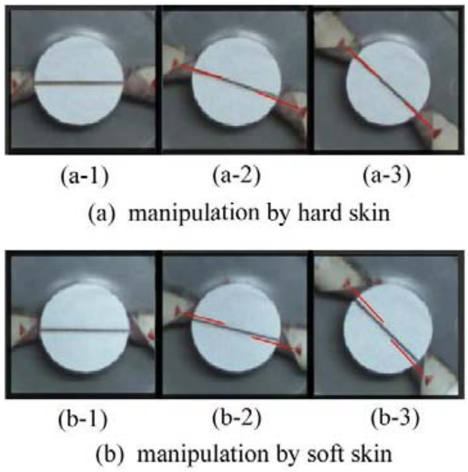


Figure 15 Experimental results

4 Conclusion

We proposed the four-fingered robot hand with skin mechanism which is able to change the softness of the surface at the finger tip. The hand has 12 DOF and shape like human hand. Thumb is designed to be able to oppose every other finger. We proposed a softness changeable mechanism with agar impression material and peltier device, which can be controlled by electric current.

We analyzed how the softness of contact area affects on the object grasping and manipulation from the viewpoint of friction, quasi-statics, and dynamics. The analyses showed that fingers with soft skin have advantages for grasping but disadvantage for manipulation. In contrast, fingers with hard skin have advantages for manipulation but disadvantage for grasping. This is also shown by fundamental experiments.

Future work will be developments of the systems in which the hand is able to automatically change its skin to appropriate softness according to the given objects, task, situation, and so on.

5 Literature

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