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Development of Anthropomorphic Robot Hand SKK Robot Hand I

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In this paper, a three-fingered anthropomorphic robot hand, called SKK Robot Hand I, is presented. By employing a two-DOF joint mechanism, called Double Active Universal Joint (abbreviated as DAUJ from now on) as its metacarpal joint, the hand makes it possible to mimic humanlike motions. We begin with addressing the motivation of the design and mention how the anthropomorphic feature of a human is realized in the design of SKK Hand I. Also, the mechanism of the hand is explained in detail, and advantages in its modular design are discussed. The proposed hand is developed for use as a testbed for dextrous manipulation. It is expected to resolve the increasing demand for robotic applications in unstructured environments. We describe its hardware construction as well as the controller structure including the preliminary results of experiments.

Key Words: Robot Hand, Anthropomorphic, DAUJ

1. Introduction

Recently, in the field of robotics a lot of progress has been made and many things considered to be impossible previously are being performed by robots. In the near future, robots are sure to be used as substitutes for a human for many tasks in our daily life. In order to replace humans, a robot should have several special abilities such as intelligence to cope with arbitrary situations, mobility to travel in the unknown environments and dexterity to manipulate objects.

Especially, to grasp or manipulate various objects in complicated environments, a dextrous hand such as that of the human may be required. However, its actual application is far from reality, although it has been studied for quite a long time.

In fact a number of researchers have developed robot hands in various fields such as mechanism, grasping, manipulation, and control, etc. The ultimate objectives of the multi-fingered robot hand is to mimic the role of human hands in specific applications.

Since the highly successful robot hands such as Stanford/JPL and Utah/MIT dextrous hand have been introduced (Salisbury, 1982; Jacobsen, 1984), various robot hands have been reported. However, few of them seem to be successfully applied to practical applications. It is because most of robot hands developed up to now are complex, bulky, and lacking in reliability.

In addition, one of the serious problems of existing robot hands is that its maintenance is very difficult or almost impossible. In the case of the robot hand, since they are constructed by assembling many parts such as various sensors, actuators and wirings, difficulties in maintenance

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may cause serious problems in the exchange and modification of parts.

In this paper we present an anthropomorphic robot hand which has three fingers and ten joints. The basic premise underlying the development of the hand is to develop mechanisms mimicking the natural motion of a human as well as having flexibility and strength of the human hand.

This paper is organized as follows. The next section describes the motivation of the research, the design of SKK Hand I is discussed in section 3. In section 4, the control architecture is explained and the preliminary results of experiments for evaluations are included in section 5. Finally the paper is concluded in section 6.

2. Motivations

Up to now several researchers have developed multi-fingered and multi-jointed robotic hands (Salisbury, 1982; Jacobsen, 1984). But most of them are not unsuitable for humanlike motions, and few of them have been successfully applied to practical applications.

As for the related researches, Bejczy utilized a joint displaying the movement similar to a metacarpal joint and applied it to a shoulder joint in his master-slave system (Bejczy, 1975). Also, Stackhouse proposed a three-DOF (degree of freedom) wrist joint using bevel gears, known as Three-Roll-Wrist joint (Stackhouse, 1979). In this mechanism, the proximal axis and the distal axis exist on the collinear line and the middle axis has some oblique angle with the other two axes. Thus, just rolling of each axis provided three-DOF rotational motions. Based on the Bejczy's mechanism, Hirose developed a joint mechanism, called Oblique Swivel joint, and applied it to a snakelike robot (Hirose, 1993). Though joint motion is kinematically restricted to a smaller range than that of the usual joint arrangements, it has an advantage of gaining high weight-to-force ratio. In 1985, Ikeda and Takanashi registered a patent called Active Universal Joint which takes most of Oblique Swivel Joint (Ikeda and Takanashi, 1987). Recently, Paljug et. al. in JPL adopted the active universal joint as the joint mechanism of the Serpentine robot (Paljug, Ohm and Hayati, 1995). In addition Asano and Nilsson have utilized two-DOF joint mechanism in their hyper DOF robot (Asano, et al. and Hitomi, 1983). But most of mechanisms described above are unsuitable for the humanlike mechanism.

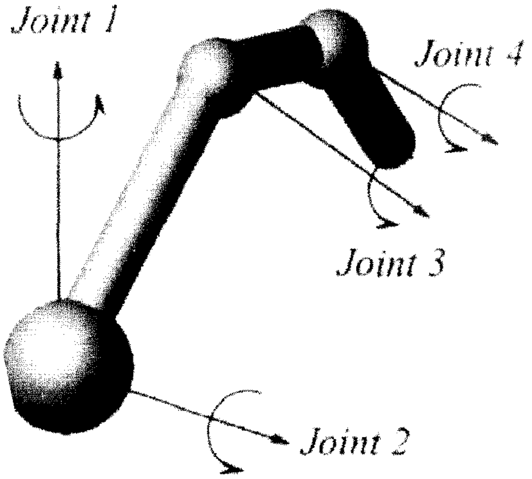

Fig. 1 Typical kinematic model of finger

In the human hand the fingers except the thumb can be modeled as a four-DOF kinematic structure, where the metacarpal joint has two DOFs and the others have one, respectively. Among these, the metacarpal joint is usually modeled with two orthogonal joints whose joint axes intersect at a single location. It may give the principal reasons that most of the robot hands intending to imitate the human hand have metacarpal joints with two orthogonal intersecting axes. But, there is a great difference between motion of the human hands and the existing robot hands. Figure 1 shows the kinematic structure of a robot hand, called Uta/MIT Hand by Jacobson (Jacobsen, 1984). It is one of the typical anthropomorphic hands with four DOFs in its finger, and its metacarpal joint is composed of two orthogonal joints. Though it aims at mimiking the humanlike motions, its joint arrangement, however, is not able to generate the anthropomorphic motion. For example, if joint 1 in Fig. 1 rotates, the orientation of the fingertip changes accordingly, which makes different part of the fingertip have contact with the object. On the contrary, the

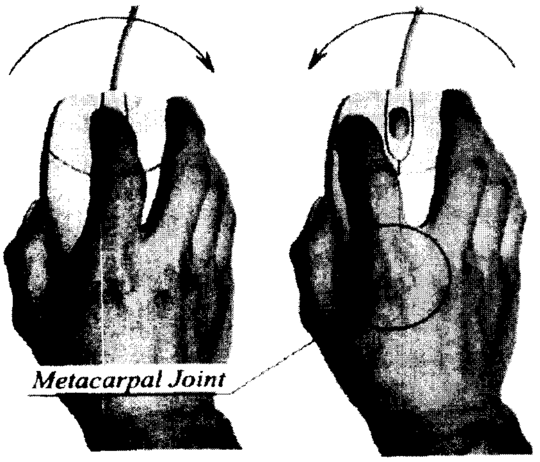

Fig. 2 Metacarpal joint motion of human

motion of the human hand is not similar to this.

If we carefully look at the swiveling motion of the index finger, it can be noted that the finger does not roll about its own axis along the link. During usual grasping or manipulating motions, the palmar side of the finger always faces up to the object. The dorsal side such as the fingernail never has contact with the object. Likewise all the other parts of the human such as limbs, legs are intrinsically unsymmetrical and there exists the distinction between the inner and outer side. Each side of the human body has its own specific function and characteristic usage.

It is an even more important feature, especially when the robot hand is required to carry on manipulating objects using its links (at times it is called whole arm manipulations). Existence of rolling makes it difficult to continuously move contact points between the finger and the grasped object. Contact may be broken during the manipulation and the grasp with links cannot persist. Basically, a robot hand is required to carry out the manipulations using links as well as the fingertip, which may be considered as a real human style robot hand.

Recently, Ryew and Choi had developed a two-DOF joint mechanism, called Double Active Universal Joint as shown in Fig. 3. In several previous reports, they have already described the characteristic features of DAUJ (Sungmoo Ryew and Hroukryeol Choi, 2001) and they applied it to a joint mechanism in several robots (Sungmoo Ryew and Hroukryeol Choi, 1999 ; Sanghoon Baik, Sungmoo Ryew, and Hyoukryeol Choi, 2001). DAUJ consists of two universal joints, and an internal oblique joint composed of a couple of splitted spherestkq ; upper and lower half spheres, which controls two-DOF joint rotation. Two half spheres meet each other in an inclined plane with angle ϕ. It is actuated by two geared DC motors with reduction mechanisms. An inner universal joint just transmits the torque of the motor to the upper half sphere. An outer universal joint is a sturdy structure for connecting two links, and it prevents relative motions between previous link and next one. DAUJ is called "oblique rotation mechanism" because it is a joint rotating around an inclined axis.

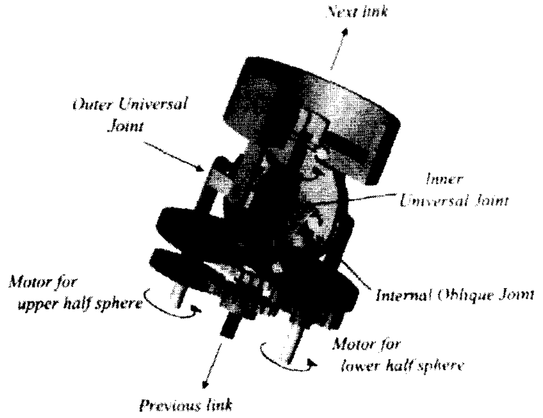

Fig. 3 Double active universal joint

Compared with existing joints with two DOFs, DAUJ is quite similar to the human joint and its advantages can be adressed as follows. In the first, it is able to ensure complete two-DOF free-of-rolling motion, which is an anthropomorphic feature as mentioned before. In the second, DAUJ gains high weight-to-force ratio which leads to structural advantage. In this paper, we present a robot hand employing DAUJ as its metacarpal joint. By employing DAUJ, an anthropomorphic, compact and moular robot hand can be realized.

3. Design of SKK Hand I

When an anthropomorphic robot hand is developed, the researchers usually begin with investigating the exoskeletal structure of a human hand and try to design a robot hand kinematically similar to that of the human. As a result, most of the robot hands consistent reported up to now have structures of three links and four DOFs for each finger. However, assuming that the contact of the finger would be considered as a three-dimensional fingertip contact, only three DOFs for each finger is enough, though some researchers insist that four DOFs be prerequisite in the view of kinematic optimality (Yoshikawa, 1985). Also, it should be noted that the human finger behaves like a three-DOF mechanism because two joints in the distal side are coupled. During the typical motions of the robot hand, it does not need more than three DOFs. Therefore, it is not necessary that the fingers of the robot hand except the thumb have more DOFs than three.

In the case of the thumb, the adequate kinematic structure is still controversal. If we closely observe the human hand on usual grasping or manipulating, the thumb plays quite a significant role. All the other fingers just cooperate with the thumb (it is called "opposition") and there are few motions being done without the thumb except special cases, for example lateral grasping that we use in smoking. According to the kinematics of the hand, at least three fingers are required to perform a stable grasping, and to carry out dextrous manipulation. The hand presented in this research consists of three fingers. The number of the fingers can be easily increased since each finger is modularized. Each finger is designed to satisfy the requirements for mainipulation and grasping. In fact, the design concept of the proposed robot hand, called SKK Hand I is started from an anthropomorphic base but the configuration of fingers is optimized in an engineering sense

3.1 Kinematic design

As shown in Fig. 4, SKK Hand I is a three-fingered robot hand with two symmetric fingers and a thumb. The thumb has four DOFs and the others three. The metacarpal joint of the fingers adopts the DAUJ, which makes it possible to integrate the actuators for the metacarpal joints in the palm for compact design of the hand.

SKK hand I consisted of three finger modules can be attached or removed easily. As shown in Fig. 4 the current arrangement shows two fingers and an opposing thumb. The number of fingers can be increased to four or five depending on the applications.

The hand weighs about 3 kg and the size of the hand is one and half times as large as the human hand including driving modules. All the driving units are included in the fingers and the palm, which makes it possible to lay wirings inside the

Table 1 Specifications of SKK Hand I

Items		Specifications
number of fingers		three
DOF		10 DOFs (1 coupled joint)
maximum Speed		20 mm/sec
maximum Force		0.9 Kgf
sensors		encoder+home sensor fingertip force sensor
actuators		DC motors
weight		about 3 Kg
size		approx. 1.5 times larger than human hand
range of motion	adduction &abduction	45°
	flexion	80°
	extension	10°

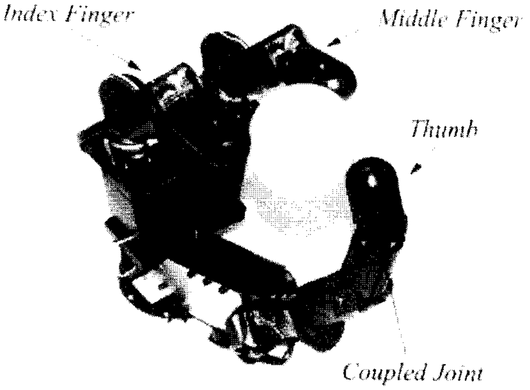

Fig. 4 SKK Hand

hand and realize compactness in design. It is very robust mechanically and able to give sufficient grasping and manipulation forces in practical usage.

As shown in Fig. 4, driving modules of the finger are embedded in the palm of the hand. The palm and two fingers (index and middle fingers) play a significant role in power grasping.

3.2 Design of finger

In the design of the finger proposed in this paper we employ DAUJ as its metacarpal joint. Though this mechanism has been continuously revised, we just introduce its characterisic features briefly in this section. As shown in Fig. 4 the thumb and the other two fingers have quite similar mechanisms except one additional coupled joint in the thumb. Thus, we mainly focus on the design of the index finger (the middle finger is exactly the same as the index finger), and the additional features of the thumb is briefly introduced.

As shown in Fig. 4, the index and middle fingers are symmetric with three DOFs because they do not solely aim at imitating the motion of the human hand. In the case of the thumb we just added one coupled joint at the distal joint. Although it looks like a four-DOF mechanism, it is actually a three-DOF one. To enhance maintainability the fingers are modularized and thus, we can easily attach or detach each finger from the hand. For reduction in its weight and easy wiring, hollow links are adopted with thickness less than 1mm. The weight of a single finger module is as light as 500g while its structural strength is kept as much high as possible. The finger module can lift up the weight as much as 0.3 Kg which is sufficient for manipulating small objects.

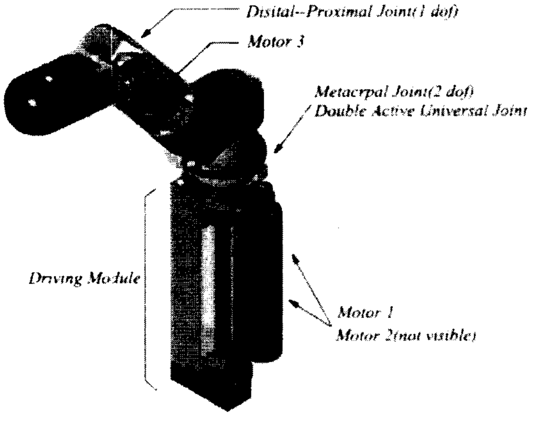

Fig. 5 Design of robotic finger

For driving the metacarpal joint, we use two DC motors. The distal joint of the finger is driven by a DC motor embedded in the distal-proximal link. The metacarpal joint of the finger can do two-DOF motions without rotating along the axis of the middle-distal link because DAUJ is applied. Thus, when it grasps an arbitrary object, the same portion of the fingertip is always maintained. As explained it is a characteristic feature similar to the human's finger. When the finger has contact with the object and explores its geometry, it is quite advantageous. The range of a finger motion goes up to 80°, 10° and 45° on flexion, extension and abduction-adduction, respectively. They are determined depending on the design of DAUJ. Also in order to simplify the structure of the finger, the number of sensors and parts have been reduced as much as possible. Sixteen bit encoders are employed to get the location information of the joint with hall sensors to detect the home position because of its excellent cost effectiveness and ease of handling. In addition a six-axis force/torque sensor (JR3) is attached at the tip of the finger with its diameter of 17 mm.

3.3 Kinematics of finger

In the previous report (Sungmoo Ryew and Hroukryeol Choi, 2001) a geometric approach to conveniently analyze the kinematics of DAUJ was proposed. In this paper its whole kinematic analysis is not intended to be mentioned in details and just parts of the analysis are introduced to help the understanding of the mechanism. We refer interested readers to the previous report.

As shown in Fig. 3, DAUJ has an internal obique joint which controls the joint rotation. It consists of an upper and a lower half sphere that meet each other in an included plane with angle ϕ. Figure 6 depicts an equivalent kinematic diagram of DAUJ by replacing the inner universal joint. As depicted in Fig. 6 the coordinate frame Σ_2 is assigned to the internal oblique joint, the reference coordinate frome Σ_0 is fixed to the base of the mechanism. Because the inner univeral joint just transmits the torque of the second motor to the joint 3, we can assign the coordinate frame Σ_3 as shown in Fig. 6 and the coordinate frame Σ_1 is attached to the rotation axis of the first motor.

In Fig. 6 we begin with representing the motion of DAUJ using Z-Y-Z Euler angles. According to Z-Y-Z Euler angle representation, the rotation of the joint can be considered to be performed in the following order: rotation about Z axis by α, rotation about negative Y' axis by β, and rotation about Z'' axis by $-\alpha$, which results in the transformation matrix

$$\begin{aligned} {}^0_3T_{ZY'Z''} &= T_z(\alpha)\,T_{Y'}(\beta)\,T_{z''}(-\alpha) \\ &= {}^0_3T(\alpha,\ \beta) \end{aligned} \tag{1}$$

where the reverse rotation $-\alpha$ about Z'' axis is due to the characteristics of the proposed mechanism that restricts rolling. L_1, L_2 and L_3 denote the link lengths and L_1 is zero in this case.

Consequently, the resultant form of Eq. (1) ${}^0_3T(\alpha,\ \beta)$ is equal to the generalized transformation matrix ${}^0_3T(\theta_1,\ \theta_2,\ \theta_3)$ obtained by the rotation of the joint. By equating, we have

$$ {}^0_3T(\alpha,\ \beta) = {}^0_3T(\theta_1,\ \theta_2,\ \theta_3) \tag{2}$$

where θ_1, θ_2 and θ_3 denote the joint variables of the inner universal joint depicted in Fig. 6. From Eq. (1) and (2), it can be assured that all the three joint variables θ_1, θ_2 and θ_3 are not independent and one of three variables, typically θ_2 can be expressed as a function of θ_1 and θ_3 such as

$$\theta_2 = -\frac{s_{13}}{|s_{13}|}\cdot\arccos\left(\frac{|c_{13}|\,w_1 + c_{13}w_2}{c_{13}w_3}\right) \tag{3}$$

where

$$\begin{gathered} w_1 = c_\phi c_{13}\sqrt{c_\phi^2 + (c_3^2 - c_1^2)\,s_\phi^2} \\ w_2 = -c_1 s_3 s_\phi^2\,(c_3 s_1 + c_1 c_\phi^2 s_3) \\ w_3 = (c_1^2 c_\phi^2 + s_1^2)\,(c_3^2 + c_\phi^2 s_3^2) \\ c_{12} \triangleq \cos(\theta_1 + \theta_2),\ s_{12} \triangleq \sin(\theta_1 + \theta_2),\ \cdots \end{gathered}$$

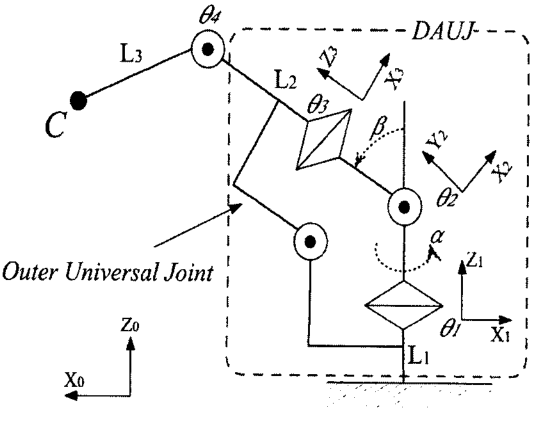

Fig. 6 Kinematic diagram of finger

From these equations, we can derive the forward kinematics of DAUJ such as

$$\alpha = \frac{\theta_1 + \theta_3}{2} \tag{4}$$

$$\beta = 2\cdot\arctan\left(\tan\phi\cdot\cos\frac{\theta_3 - \theta_1}{2}\right) \tag{5}$$

and the inverse kinematics is given by

$$\theta_1 = \alpha \pm \arctan\left(\cot\phi\,\tan\frac{90-\beta}{2}\right) - \pi \tag{6}$$

$$\theta_3 = \alpha \mp \arctan\left(\cot\phi\,\tan\frac{90-\beta}{2}\right) - \pi \tag{7}$$

where $\phi = 22.5°$ is the oblique angle. From Eqs. (4) ~ (7), we can say that the robotic finger may be modeled as a three-DOF system with joint variables α, β and θ_4 as shown in Fig. 6.

To solve the kinematics of the whole finger let us represent the overall transformation matrix from the base to the tip of the finger ${}^0_5T$ such as

$$ {}^0_5T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{8}$$

Then, we have

$$ {}^0_5T = {}^0_\alpha T {}^\alpha_x T {}^x_4 T {}^4_5 T \tag{9}$$

where,

$$ {}^0_\alpha T = \begin{bmatrix} c_\alpha & -s_\alpha & 0 & 0 \\ s_\alpha & c_\alpha & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$
{}^{\alpha}_{x}T=\begin{bmatrix} c_x & -s_x & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s_x & -c_x & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{x}_{4}T=\begin{bmatrix} c_4 & -s_4 & 0 & L_2 \\ s_4 & c_4 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{4}_{5}T=\begin{bmatrix} 1 & 0 & 0 & L_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

and, χ is $\beta+\delta$ (δ is the offset angle of a robotic finger to adjust the range of extension).

From Eq. (9) the forward kinematic solutions can be computed as follows.

$$
\begin{aligned}
r_{11}&=C_\alpha C_{x4}\\
r_{12}&=-C_\alpha S_{x4}\\
r_{13}&=-S_\alpha\\
r_{21}&=S_\alpha C_{x4}\\
r_{22}&=-S_\alpha S_{x4}\\
r_{23}&=-C_\alpha\\
r_{31}&=-S_{k4}\\
r_{32}&=-C_{x4}\\
r_{33}&=0\\
p_x&=L_2C_\alpha C_x+L_3C_\alpha C_{x4}\\
p_y&=L_2S_\alpha C_x+L_3S_\alpha C_{x4}\\
p_z&=-L_2S_x-L_3S_{x4}
\end{aligned}
\tag{10}
$$

From Eq. (10), we can derive the inverse kinematics of the robotic finger such as

$$\alpha=\arctan 2(p_y,\ p_x) \tag{11}$$

$$\chi=\arctan 2(s_x,\ c_x) \tag{12}$$

$$\theta_4=\arctan 2(s_4,\ c_4) \tag{13}$$

where

$$
\begin{aligned}
c_4&=\frac{1}{2L_2L_3}[p_x^2+p_y^2+p_z^2-L_2^2-L_3^2]\\
s_4&=\pm\sqrt{1-c_4^2}\\
c_x&=L_3s_4p_z-(L_2+L_3c_4)(c_\alpha p_x+s_\alpha p_y)\\
s_x&=L_3s_4(c_\alpha p_x+s_\alpha p_y)+(L_2+L_3c_4)p_z
\end{aligned}
$$

Also we can derive Jacobian matrix such as

$$
J=\begin{bmatrix} -L_2S_\alpha C_x-L_3S_\alpha C_{x4} & -L_2C_\alpha S_x-L_3C_\alpha S_{x4} & -L_3C_\alpha S_{x4} \\ L_2C_\alpha C_x+L_3C_\alpha C_{x4} & -L_2S_\alpha S_x-L_3S_\alpha S_{x4} & -L_3S_\alpha S_{x4} \\ 0 & -L_2C_x-L_3C_{x4} & -L_3C_{x4} \end{bmatrix} \tag{14}
$$

4. Control System

Figure 7 illustrates the structure of the control system developed for SKK Hand I. In this system a six-DOF industrial robot(Samsung, FARAMAN-As1) is employed as the arm and SKK Hand I is attached on the wrist of the arm. The system is controlled by a PC based controller. As the main controller, two personal computers are

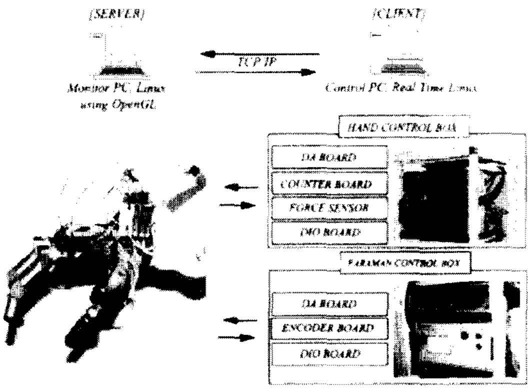

Fig. 7 Hardware system

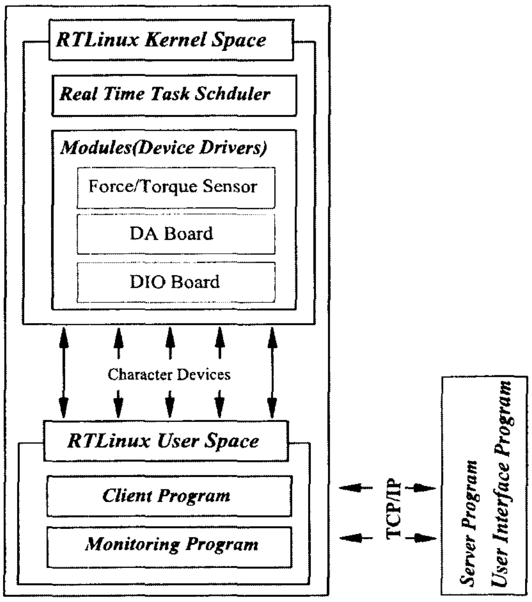

Fig. 8 Software structure

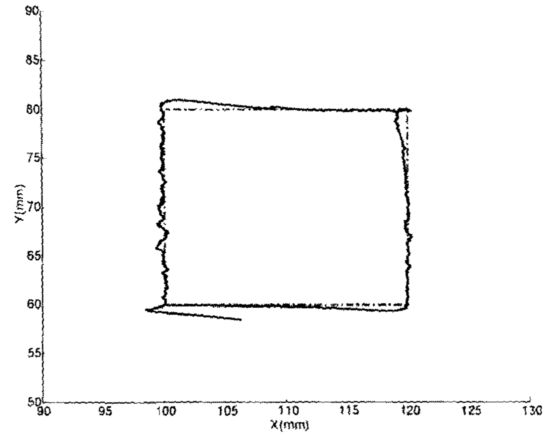

Fig. 9 Trajectory of rectangular motion

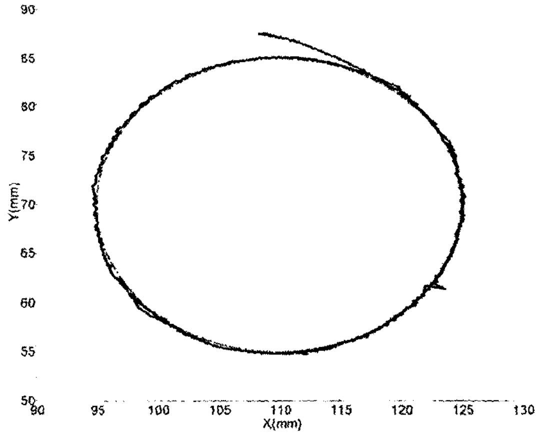

Fig. 10 Trajectory of circular motion

used and RTLinux(realtime linux, rt-kernel 2.2.14) is applied as the operating system. These computers communicate with each other via Ethernet based on the TCP/IP protocol.

As shown in Fig. 8 the software architecture is divided into two parts such as the user space and the kernel space. The user space provides several functions for user interface such as monitoring and the kernel space function includes schedulers, driver programs for various acquisition boards, respectively.

In this system various grasping and manipulation algorithms can be implemented and new strategies for dextrous manipulation, coordination of hand and arm will be tested. This system can be used as the test bed for the dexterous manipulation.

5. Preliminary Experiments

In the preliminary experiments the performance of the position control was tested. In this experiment, the finger tip was commanded to follow a given trajectory such as rectangular and circular trajectories. A simple PD control scheme was applied and the positions were measured. Fig. 9 represents control performance in the case of a rectangular trajectory, where the solid line denotes the actual trajectory of the fingertip and the dotted line represerts that of the commanded ones. Here the center of the fingertip is considered as the point to be measured. In this experiments the total cycle time was 4 seconds. As shown in Figs. 9 and 10, the finger tracks the rectangular and circular trajectories reasonably well.

6. Conclusion

A new anthropomorphic robot hand, SKK Hand I was developed. The achievements of the proposed hand are deserved to be highly evaluated on the following terms. First, the hand can completely simulate humanlike metacarpal motions, which gives several advantageous aspects in actual applications. For example, it can achieve highly complicated grasping and manipulating motions because the contact points does not change a lot during manipulation. Therefore in the case of utilizing tactile sensors, only small size of tactile sensors may be enough and it is not necessary to cover up the whole surface of the fingertip. In the second, this hand displays a lot of achievements compared to the previous ones in the engineering sense. It removed complicated wiring and the integrated design of driving components and the palm was realized. According to its completeness SKK Hand I is considered a quite successful one and to be used as a testbed for dextrous manipulation as well as a dextrous end effector of humanlike arm.

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