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Paper:

Mechanism Design of Anthropomorphic Robot Hand: Gifu Hand I

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This paper presents an anthropomorphic robot hand Gifu Hand I, to be used as a platform of robot hand for the study of dexterous manipulation. To perform grasping and manipulation like a human, the Gifu Hand I includes five fingers whose actuators are servomotors built in the palm and fingers. A thumb has four degree-of-freedom (DOF) and four joints, and fingers have three DOF and four joints. Two axes of joints near the palm cross orthogonally at one point like the human hand. The design concept of the anthropomorphic robot hand is presented and mechanisms and specifications of the developed robot hand are shown.

Keywords: Robot hand, Anthropomorphic hand, Mechanical design, Humanoid.

1. Introduction

Robots used in hazardous environments are often required to perform complex multipurpose tasks communicating with human operators. In environments such as subsea pipeline inspection and repair, telesurgery, and construction in space, a robot hand must be anthropomorphic in both geometry and size. The anthropomorphic robot hand enables minute work instead of astronauts wearing gloves and undertaking dangerous tasks in hostile environments. The anthropomorphic robot hand is also used as a prosthetic for the handicapped. Many multi-fingered robot hands (the Stanford/JPL hand by Salisbury et al.[1]), the Utah/MIT hand by Jacobson et al.[2]), and the Anthrobot hand by Kyriakopoulos et al.[3])) have been developed. These robot hands are driven by actuators such as servomotors or pneumatic cylinders, located away from the robot hand using tendon cables. In this tendon method, the relation between the joint angle and the actuator displacement is nonlinear because of the interference between tendon cables, and it is very difficult to control the joint angle accurately because of the elasticity of tendon cables. Motion of the robot arm is obstructed by actuators and tendon cables when the robot hand is attached to the robot arm.

To solve these problems, robot hands have been developed[4-7]) whose actuators are servomotors built in the palm, thumb, and fingers the built-in servomotor method. The Belgrade/USC hand[4]) has five fingers and four motors, two motors for the thumb and two for the fingers. Since this hand has only four DOF, it only provides simple grasping rather than dexterous manipulation. The Omni hand by Rosheim[5]) has three fingers, each with three DOF and three joints. The NTU hand by Lin et al.,[6]) has five fingers. In the NTU hand, the thumb and forefinger have four DOF and four joints and other fingers have three DOF and three joints. The Waseda hand by Morita et al.[7]) has five fingers The thumb of the Waseda hand has four DOF and four joints and the other fingers have three DOF and three joints. All these hands have servomotors built in the palm and fingers. But they have not a mechanism such that two joint axes near the palm cross orthogonally at one point and all fingers have four joints like the human fingers.

We present the concept and mechanical specifications of the developed anthropomorphic robot hand, Gifu Hand I. Gifu Hand I has five fingers by the built-in servomotor method. Since the thumb has four DOF and four joints, the fingers have three DOF and four joints, and two axes of joints near the palm cross orthogonally at one point like the human finger, the Gifu Hand I performs grasping and dexterous manipulation like the human hand.

2. Design Concept

Our goal is a hand used as a standard robot hand for the study of grasping and dexterous manipulation. The Gifu Hand I is compact, light-weight, and anthropomorphic in both geometry and size. It performs grasping and manipulation like the human hand. The design concept is as follows:

(1) Size

It is desirable to resemble the robot and human hands in size for skillful manipulation. The robot hand is similar to a bigger human hand. The proportions of the link lengths in finger design are based on that of the human hand.

(2) Finger DOF

The human finger is modeled as a link mechanism with four joints[5]). All joints of the thumb move independently. In fingers, the first to third joints move independently while the fourth joint engages with the third joint. This means that the thumb is required to be more dexterity than the fingers. Grasping by the thumb is stronger than that of the other fingers. The first and the second joints of the human fingers cross almost orthogonally at a point. A number of joints and a motion DOF in the robot hand are similar to those of the human hand.

(3) Opposability of the thumb

The human thumb is opposable to fingers, enabling the hand to manipulate objects dexterously. The robot hand must also have opposability.

(4) Force sensor

The human fingers includes tactile sensors and force sensors enabling dexterous manipulation of objects. Each fingertip of Gifu Hand I has a six-axes force sensor for compliant manipulation.

(5) Built-in servomotor method

It is important that motion of the robot arm not be disturbed by the robot hand and the robot hand be easily attachable to the robot arm. The built-in servomotor method is suitable for these aims. The gear transmission is to be highly stiff for precise position control, and must consist of highly stiff gears such as a satellite gear and/or a bevel gear instead of low stiff gears such as a harmonic drive gear.

(6) Unit design of the finger

Easy maintenance and easy manufacture of the robot hand are important, so each joint must be modular and each finger must be a unite. Due to the unit design of the finger, hands having from two fingers to five fingers are made easily.

3. Hand Mechanism

Mechanisms of the thumb and the other fingers based on our design concept are shown in **Fig. 1(a)** and **Fig. 1(b)**. Servomotors and joints are numbered from the palm to the fingertip. Each servomotor (Maxson DC motor, Interelectric AG) has a magnetic encoder with 16 count/revolution to sense the motor angle. **Fig. 2** and **3** shows Gifu Hand I. Specifications are given in **Table 1**.

3.1. Finger Mechanism

The Gifu Hand I has five fingers like the human hand.

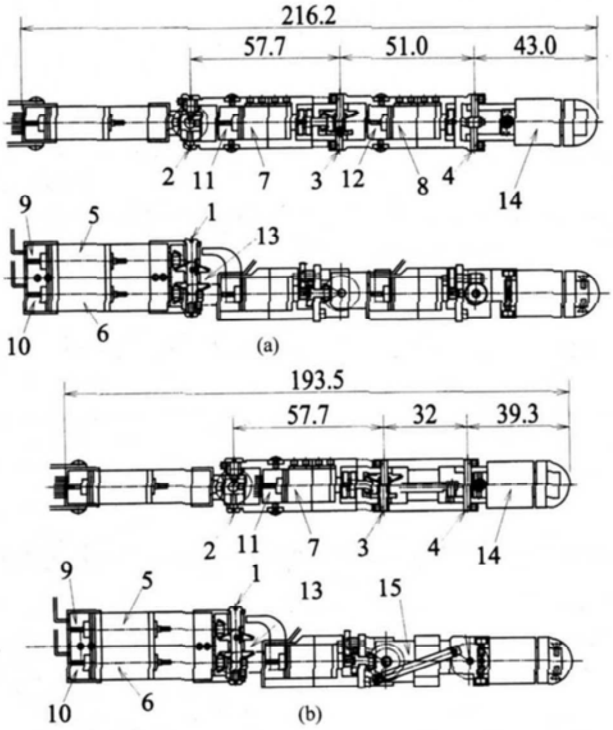


Fig. 1. Mechanisms of the fingers. (a): The thumb, (b): The finger except the thumb.

The thumb has four joints and four DOF. Each finger has four joints and three DOF. The Gifu robot hand has 20 joints and 16 DOF in total, similar to the number of joints and DOF of the human hand. Fingers have following features:

(1) United mechanism of the finger

Each joint of the Gifu Hand I is designed as a module. A mechanical difference between the thumb and fingers is that the fourth joint of the thumb is driven by a servomotor and a gear train in the second segment of the thumb while the fourth joint of the fingers is driven through a planar

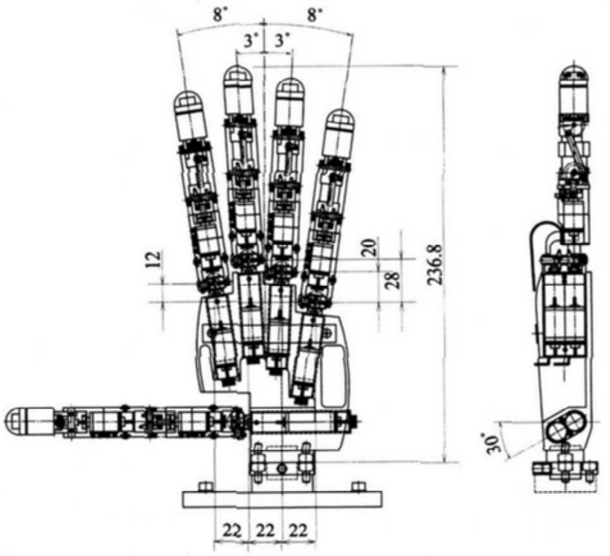


Fig. 2. Structure of the Gifu Hand I.

Fig. 3. Developed hand.

Table 1. Specifications of the Gifu Hand I

Weight of the finger except the thumb		167 [gf]
Weight of the thumb		212 [gf]
Total weight of Gifu Hand I		1226 [gf]
Exerted force at the fingertip		250 [gf]
Gear ratio	1st joint	134.98
	2nd joint	67.49
	3rd joint	73.43
	4th joint of the thumb	64.62
Band width	1st joint of the thumb	9.1 [Hz]
	3rd joint of the thumb	6.6 [Hz]
	4th joint of the thumb	6.7 [Hz]

four-bar linkage mechanism in the second segment of the finger.

Thus the DOF of the thumb is one more than that of fingers. Replacement of the finger is easy because each finger is designed as a united mechanism consisting of modular joints.

(2) Asymmetrical differential gear

The rotation of the first and second joints is controlled independently through an asymmetrical differential gear by the first and second servomotors. This asymmetrical gear enables the second joint to be placed near the surface of the palm and the axes of the first joint and the second joint to be orthogonal. Since the mobile range of the second joint is large enough, the kinematics of robot hand is similar to that of the human hand.

(3) Planar four-bar linkage mechanism

In the human hand, the motion of the fourth joint of the fingers except the thumb engages with that of the third joint. A measurement of the relation between the third and fourth joint angles of the forefinger of the human is shown in **Fig. 4**. The fourth joint angle engages with the third joint angle almost linearly. In Gifu Hand I, the fourth joint is driven by a planar four-bar linkage mechanism shown in **Fig. 5(a)** and the third servomotor to make the engagement. In this planar four-bar linkage mechanism, a relation between a displacement of the third joint q_3 and a displacement of the fourth joint q_4 is given as follows:

$$l = ((r_3 \sin(q_{3_0} + q_3) + r_4 \sin(q_{4_0} + q_4))^2 + (a + r_3 \cos(q_{3_0} + q_3) - r_4 \cos(q_{4_0} + q_4))^2)^{\frac{1}{2}} \quad \cdots \quad (1)$$

where a is a length of the second finger segment, r_3 and r_4 are link radiuses of the third and fourth joints, q_{4_0} and q_{3_0} are initial angles of the planar four-bar linkage mechanism, and l is a length of the connected link given by

$$l = ((r_3 \sin q_{3_0} + r_4 \sin q_{4_0})^2 + (a + r_3 \cos q_{3_0} - r_4 \cos q_{4_0})^2)^{\frac{1}{2}} \quad \cdots \quad (2)$$

By substituting equation (2) into equation (1), q_4 is represented as a function given by

$$q_4 = f(a, r_3, r_4, q_{3_0}, q_{4_0}, q_3) \quad \cdots \quad (3)$$

Though q_4 is nonlinear to q_3, parameters of the planar four-bar linkage were set such that q_4 is nearly linear to q_3 as follows; a=32 mm, r_3=r_4=7 mm, q_{3_0}=30degree, q_{4_0}=70 degree. As a result, the relation between q_4 and q_3 is shown in **Fig. 5(b)**. A maximal difference from linear displacement is 1.27 degree. Though computation of equation (3) is relatively complex, a requirement of computation of q_4 be reduced by using a table-lookup and interpolation.

(4) Compactness and light-weight

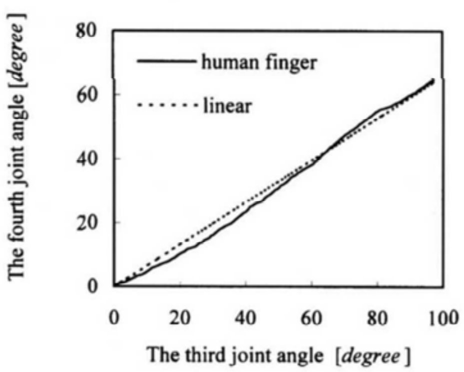
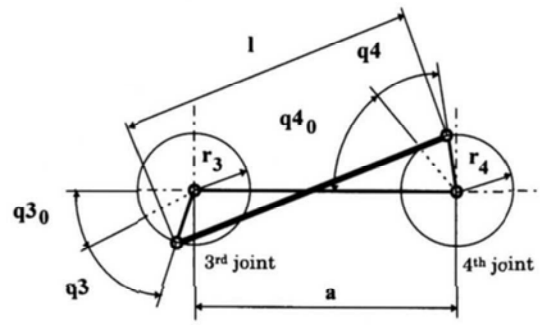
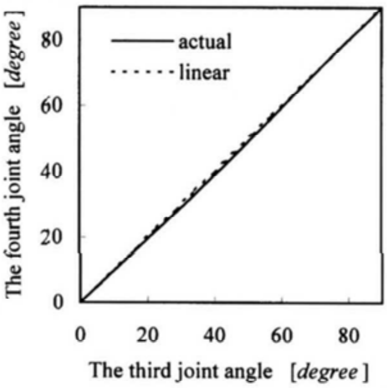


Fig. 4. Relation between 3rd and 4th joint angles of human forefinger.



(a) Skeleton



(b) Relation between the third and fourth joint angles of the Gifu Hand I.

Fig. 5. Planar four-bar linkage mechanism.

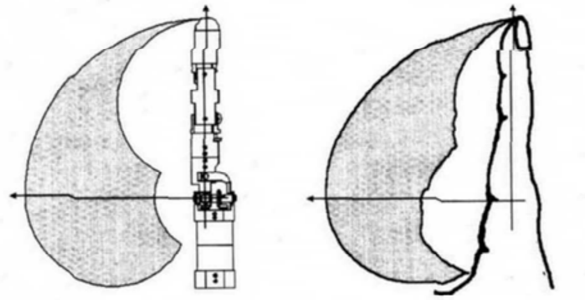
For compactness and light-weight, the servomotor and the frame are united, and a material of gears is a titanium alloy (brass in the first prototype)[8]. The thumb mechanism weighs 212 g, and that of fingers 167 g. A total weight of the robot hand is about 1.2 kg. We think the weight of Gifu Hand I is light enough to be mounted on the robot arm.

(5) Six-axes force sensor

Each fingertip has a six-axes force sensor (NANO sensor, BL AUTOTEC Corp.). Compliant grasping by fingertips is possible because force on the fingertip and an operational point of the force are detected. The six-axes force sensor is easily exchanged for a dummy fingertip.

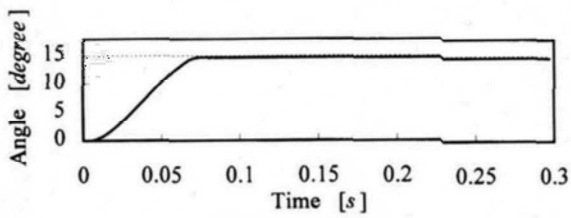
(6) Mobile space

The net length of finger is 129 mm. This is similar to

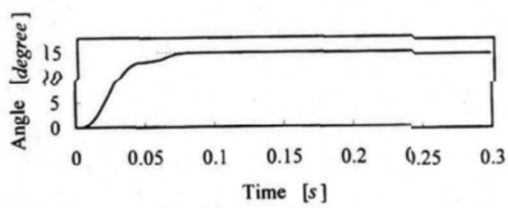


(a) Forefinger of Gifu Hand I (b) Forefinger of human

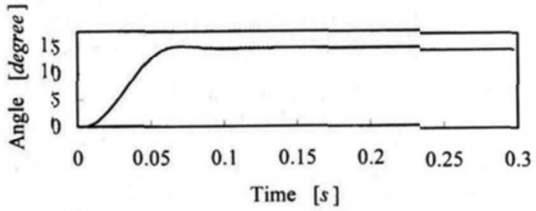
Fig. 6. Mobile space of finger



(a) The 1st joint



(b) The second joint



(c) The third joint

Fig.7. Step responses of the finger except the thumb

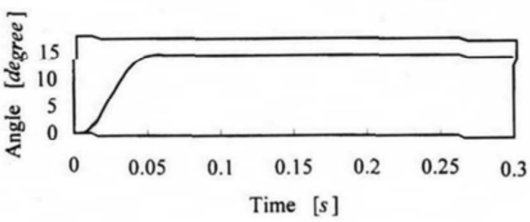


Fig. 8. Step response of the fourth joint of the thumb

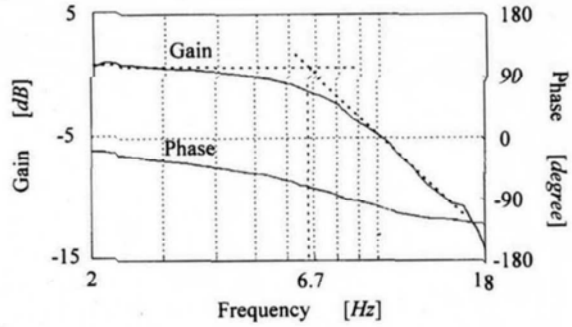


Fig. 9 Frequency characteristics of 3rd joint

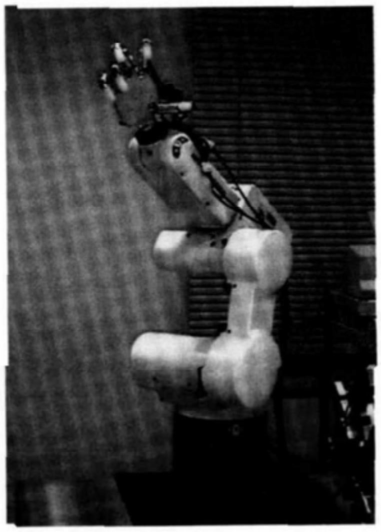


Fig. 10. Robot arm with the Gifu Hand I

the size of the bigger human hand. Mobile spaces of fingertips of the developed finger and the human are shown in **Fig. 6(a)** and **Fig. 6(b)**. The human finger is drawn the same size as the robot finger to confirm geometrical similarity of the human and robot fingers. These are alike.

(7) Response

Step responses of the finger by PD control are shown in **Fig. 7**. The joint angle velocity is obtained as a digital derivation of joint displacement. **Fig. 7(a)**, **(b)**, and **(c)** are responses of the first, second, and third joints. A step response of the fourth joint of the thumb is shown in **Fig. 8**. Raised time of each step response is less than 0.07 second. Bandwidths of frequency-gain characteristics of the 1st joint and the 4th joint of the thumb by velocity feedback control are 9.1 Hz and 6.7 Hz and of the 3rd joint of the finger 6.6 Hz. As example, frequency characteristics of the 3rd joint are shown in **Fig. 9**. The responsibility of the developed hand is superior to that of the human finger.

(8) Grasping force

The developed finger mechanism exerts 250 g-f at the fingertip, enabling Gifu Hand I to grasp up to 1.2 kg-f with five fingers.

3.2. Palm Design

Feachures of the palm are as follows:

(1) Allocation of fingers

To make the robot hand more anthropomorphic in geometry, an allocation of fingers is designed referencing the average of five human adult hands. Two criteria for design measures are adopted an angle between the first segment of each finger and the center line of hand that is set in the middle of the third and fourth fingers. And the length between the first joints of each finger and the fifth finger that is a reference point.

By taking the difference of the size of robot and human fingers into account, the actual length was designed as not disturbing the lateral motion of each finger under condition of unchanged measurement criteria.

The thumb is located leaning at 30 [degree] against the palm such that the thumb is opposable to all fingers.

(2) Easy attachment to Robot Arm

Gifu Hand I can be attached to a commercial robot arm, DENSO robot VS-6354BM model made by DENSO Corporation (**Fig. 10**). By exchanging the wrist attachment, the Gifu Hand I is attached to another robot arm, making possible research on robot tasks using the robot arm and the anthropomorphic robot hand together.

(3) Palm

The palm is made from an aluminum ingot as a unit. By remaking only the palm, an another hand such as a three-fingered hand can be made easily.

4. Conclusions

We presented the design concept and features of an anthropomorphic robot hand, Gifu Hand I, to be used as a standard anthropomorphic robot hand. Gifu Hand I uses the built-in servomotor method, and its number of DOF is similar to that of the human hand. This hand has nonnegligible backlash, but the backlash will be reduced by a modified mechanical design in future. We plan to study control for the developed hand.

Acknowledgments

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