IEEE/RSJ Intern. Conf. on Intelligent Robots and Systems (IROS 2000) Japan, Oct. 30 - Nov. 5, 2000.

Design of the TUAT/Karlsruhe Humanoid Hand

Naoki Fukaya and Shigeki Toyama

Department of Mechanical System Engineering,
Tokyo University of Agriculture and Technology, Japan
fukaya@cc.tuat.ac.jp, toyama@cc.tuat.ac.jp

Tamim Asfour and Rüdiger Dillmann

Department of Computer Science,
Institute for Control and Robotics,
University of Karlsruhe, Germany
asfour@ira.uka.de, dillmann@ira.uka.de

Abstract

The increasing demand for robotic applications in dynamic unstructured environments is motivating the need for dextrous end-effectors which can cope with the wide variety of tasks and objects encountered in these environments. The human hand is a very complex grasping tool that can handle objects of different sizes and shapes. Many research activities have been carried out to develop artificial robot hands with capabilities similar to the human hand. In this paper the mechanism and design of a new humanoid-type hand (called TUAT/Karlsruhe Humanoid Hand) with human-like manipulation abilities is discussed. The new hand is designed for the humanoid robot ARMAR which has to work autonomously or interactively in cooperation with humans and for an artificial lightweight arm for handicapped persons. The arm is developed as close as possible to the human arm and is driven by spherical ultrasonic motors. The ideal end-effector for such an artificial arm or a humanoid would be able to use the tools and objects that a person uses when working in the same environment. Therefore a new hand is designed for anatomical consistency with the human hand. This includes the number of fingers and the placement and motion of the thumb, the proportions of the link lengths and the shape of the palm. It can also perform most part of human grasping types. The TUAT/Karlsruhe Humanoid Hand possesses 20 DOF and is driven by one actuator which can be placed into or around the hand.

1. Introduction

Robots of the current generation have been used in fields isolated from the human society. They suffer major shortcomings because of their limited abilities for manipulation and interaction with humans. Humanoid Robots are expected to exist together with human beings in the everyday world such as hospitals, offices and homes. An intelligent behavior of a robot with human-like skills can only be achieved through the permanent interaction between cognition components, the robot system itself and a human operator who demonstrates typical actions. In cooperation with human beings humanoid robots should react human friendly. Therefore, they need a lightweight body, high flexibility, many kinds of sensors and high intelligence. They have to be adaptive and capable of performing tasks in changing environment. This requires them to be highly flexible, autonomous and adaptive to new situations. The design of such humanoid robots requires a high extent of integration of mechanical, hardware and software components.

At the Forschungszentrum Informatik Karlsruhe (FZI) we develop the humanoid robot ARMAR [1], which should be able to assist in workshops or home environments. At the group of the Tokyo University of Agriculture and Technology (TUAT) we developed an artificial arm for handicapped people [4]. The modeling of a sophisticated hand is one of the challenges in the design of humanoid robots and artificial arms. Firstly, it is difficult to place the complex mechanism of the hand into a narrow space. Besides, the weight of the hand has a great impact on the actuators used to construct the robot arm or the artificial arm. In fact, the weight of the hand increases the power consumption of the robot, gives a load on every joints and causes unstable behavior of the arm.

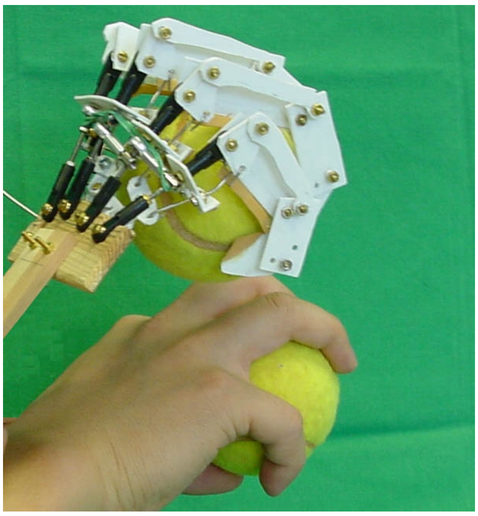

Fig. 1 The TUAT/Karlsruhe humanoid hand

Another problem is the control task to grasp various objects. Some robot hands require many actuators to be dexterously moved [5]-[10]. However, the control system of the humanoid robot becomes more complicated if more actuators are additionally used for the hand design. This is a key aspect for the artificial arm because a handicapped person might not be able to control a complex hand mechanism with many actuators.

For this reason, we propose to develop a lightweight hand driven by a single actuator. We call it the TUAT/Karlsruhe humanoid hand. To this end we adopt a new mechanism for the cooperative movement of finger and palm joints. Fig. 1 shows a typical example of grasping performed by the humanoid hand and the human hand.

Starting from the mechanics concept of the humanoid hand, we show the way typical movements of the human hand can be realized by the humanoid hand. We also report early experimental results about grasping objects.

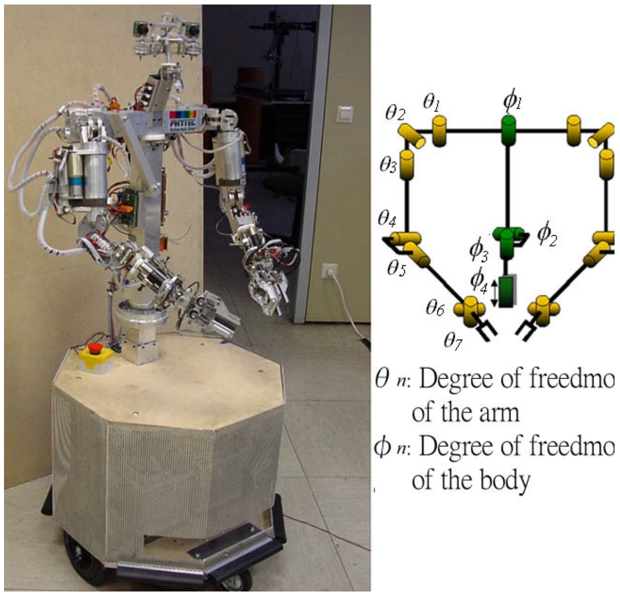

Fig. 2 The humanoid robot ARMAR

2. Humanoid robot and artificial arm

2.1. Humanoid robot ARMAR

We developed the autonomous mobile humanoid robot ARMAR with a torso, two anthropomorphic arms with simple grippers. For the detection of the environment a head equipped with a stereo camera system is used. The aim of our research is the programming of the manipulation tasks of ARMAR by a motion mapping between the robot and the person, who demonstrates the task [2]. Through the direct interaction between a human operator and the robot, natural movements of the arms and of the torso of ARMAR are generated. Based on this, skills should be gained as part of different manipulation tasks. In the following we report a detailed description of the mechatronics concept and the kinematics of ARMAR.

Mechanically, the humanoid robot ARMAR consists of an autonomous mobile wheel-driven platform, a body with 4 DOF, lightweight two-arm system with simple grippers and a stereo camera head. The total weight of ARMAR is about 45kg. The mobile platform consists of two active driven wheels fixed in the middle of an octagonal board and other two wheels as passive stabilizers. The maximum velocity of the platform is about 1 m/s. The torso can be bent forward, backward and sideward. We also installed a telescopic joint in the torso. With this joint the total height of the robot can be increased by 40 cm.

For the dual arm system, we designed two arms, each having 7 DOF and a length of 65 cm (including the gripper). Since the robot should support a simple and direct cooperation with the human, the physical structure (size, shape and kinematics) of the anthropomorphic arm is developed as close as possible to the human arm in terms of segment lengths, axis of rotation and workspace. The anthropomorphic arm design is based on a simplified kinematics model, which approximates the kinematics, kinetic characteristics of the human arm.

The motor control of the robot has been designed to be modular. Currently, the robot is controlled by C-167 micro-controller and standard PCs (PC/104). The micro-controllers are coupled with special power cards, which control 4 motors. The micro-controller boards are connected via CAN-Bus with a maximal transfer rate of 1 Mbit/s to the PC. For real-time requirements the real-time operating system RTLinux is used. Modules like collision avoidance, trajectory planning, data interpretation from every sensor directly coupled with the micro-controller are running on the PC. The PC is connected via wireless Ethernet to a PC-network. Programs for simulation and special GUIs for the monitoring and the control of ARMAR are running on these external PCs. For more details see [2].

2.2. An artificial arm by using a spherical ultrasonic motor

In an artificial arm, which uses an electromagnetic motor, multiple degrees of freedom of motion are obtained by combining several motors with a single degree of freedom of motion into a complex transmission mechanism. Consequently, the arm becomes too large and heavy and thus it will be a burden for users. To solve this problem, efforts have been expended to develop novel actuator. We have also developed a high output torque type ultrasonic motor for an elbow joint and a shoulder joint. Since it consists of two stators and one rotor in one

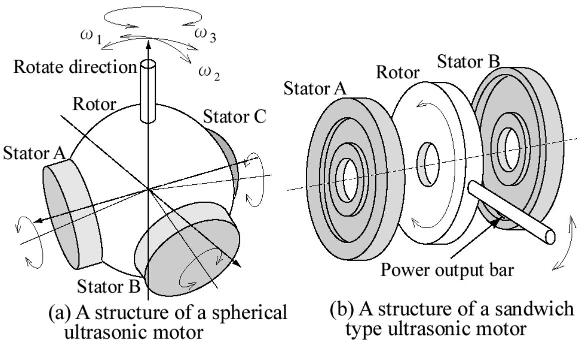

Fig. 3 Assembled ultrasonic motors

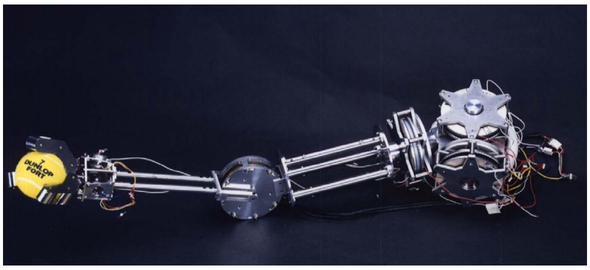

Fig. 4 An artificial arm by using the spherical ultrasonic motor

unit it is realized as a sandwich type ultrasonic motor [3]. This sandwich type ultrasonic motor produces twice as high torque output as the same size conventional ultrasonic motor. Fig. 3 shows the structure of the spherical ultrasonic motor and the sandwich type ultrasonic motor.

In addition, we assembled these motors into an artificial arm. Fig 4 shows a picture of the artificial arm that uses both types of ultrasonic motors with a simple gripper. It has one spherical ultrasonic motor for the wrist joint, one sandwich type ultrasonic motor for the elbow and three sandwich type ultrasonic motors for the shoulder joint. Consequently, the artificial arm has 7 DOF and represents a good approximation of the human arm. The advantages of the arm are small size, lightweight and high torque at low velocity compared with conventional ones. Then, the artificial arm has enough space that can be used to include sensors or controllers. With a few further assignments of output characteristics, it is possible to fulfill the demands for using the arm for a handicapped person.

3. The human hand

At this stage, it is clear what kind of model is suitable for grasping various kind of objects.

3.1. Types of grasping

Fig.5 clearly shows the typical grasping types of

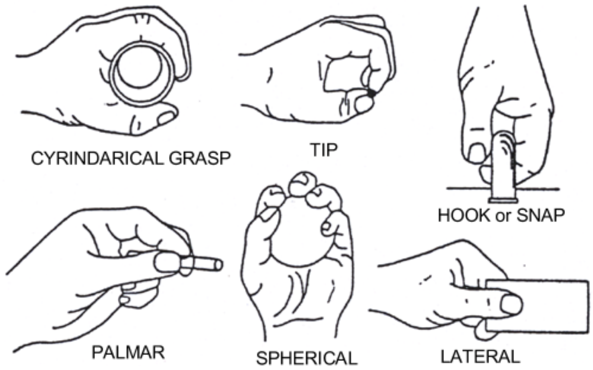

Fig. 5 Typical human grasping

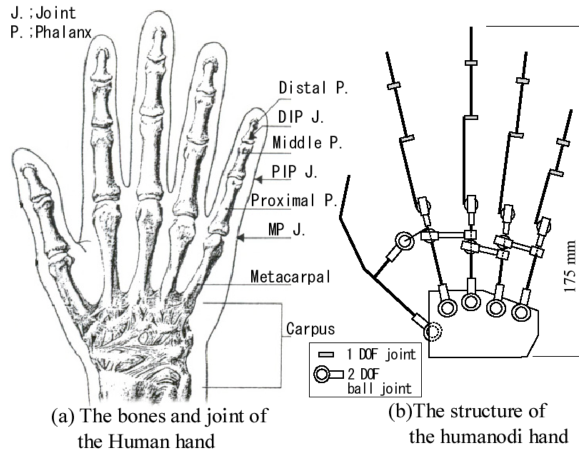

Fig. 6 Structure of the human hand and the humanoid

various objects. The six basic types of hand grasping are namely Cylindrical Grasp, Tip Grasp, Hook or Snap Grasp, Palmar Grasp, Spherical Grasp and Lateral or Keypinch Grasp. From photographic observation of the grasping patterns naturally assumed by individuals when picking up and holding common objects used in everyday life, three types of grasping were selected by Keller, et al.[12], namely palmar, tip and lateral grasping.

Based on the frequency of occurrence of each of these types, their investigation proved that the palmar and lateral grasps are dominant over the other grasping types. Hence, most artificial hands constructed today are able to only duplicate these two grasping types. This would limit the ability of an amputee for grasping various objects.

3.2. Operation of the finger and the palm

One of the main characteristics of the human hand is the capability of conformably grasping objects with various geometries. Now we are thinking about the grasping task of a spherical object. Every finger touches evenly a spherical surface when using spherical grasping.

Besides, we observe that the little finger and the index finger touch the side surface of the grasped object. This is caused by abduct or adduct action of the metacarpal-phalangeal (MP) joints and the transformation of the palm part in the tuck of the object. For this reason, the position of the MP joints of the little and the ring fingers move forward from the normal position.

We do not think about the position of fingers and palm when we want to grasp some object. We are unconscious of using the palm part and abduct or adduct motions of the MP joints. Because we already know instinctively which position is the best for stable grasp and for saving grasping force. This matter has an important meaning, namely our hand and fingers are automatically moved when we want to stable grasp an object, and the grasping force of each finger becomes even. We simultaneously make adjustments of the position of every finger and of the contact position of the palm.

From the above discussion we can conclude that the design requirements for the hand may be satisfied with each finger and the palm acting together in a coordinated group, being independently controlled and making self-adjustment of the position of fingers and palm.

4. Humanoid hand

Based on this research work we constructed an experimental model of the humanoid hand. We considered the size of a healthy 27 years old Japanese man, his height is 165 cm, and his weight is 55 kg. The humanoid hand has similar geometry; it has a length of 175 mm measured from the bottom to the fingertip of the middle finger and a width of 130 mm. Its weight is 125 g. Through the operation of the palm, the link mechanism and the adduction of the MP joints, the grasping forms of the humanoid hand become similar to that of the human hand.

4.1. Mechanical design of the four fingers

Figure 6(a) shows a clear, rather complex picture of the skeletal structure of the human hand with the wrist. The first four fingers of the human hand are somehow identical, and each one consists of three joints with four degrees of freedom. The proximal joint or the joint closest to the palm is called the metacarpal-phalangeal (MP) joint and has two degrees of freedom. These joints provide an adduction-abduction movement over a range of about 30[deg] and flexion-extension of about 120[deg]. The next two joints of the human finger are the interphalangeal joints (IP), which are revolute with one degree of freedom each and a range of motion of approximately 90[deg] about their axis of motion [13].

Then we constructed a palm using a ball-joint rod with 2 DOF. The index and middle metacarpal rods are rigid on the base of a plate which is connected to the wrist. The metacarpal rods of the ring and little fingers are free movable like the human palm and are connected with short ball-joint rods like tendons. Thus, each metacarpal joint has 2 DOF (Fig. 6(b)).

The index, middle, ring and little fingers have a complex link mechanism. Fig 7 shows the way this link mechanism works. To grasp an object, the link-rod A pulls the link-plate D and the finger moves and keeps its form. If the proximal part touches an object, the following happens: the link-plate D moves independently while the middle proximal part is moved by the link B. The link C attached to the proximal part pulls the distal proximal part. Finally, the finger curls around the object with a small grasping force.

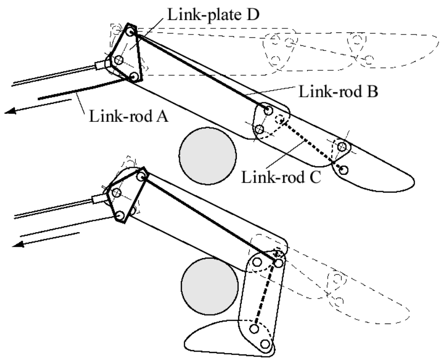

Fig. 7 Mechanical works on the four fingers

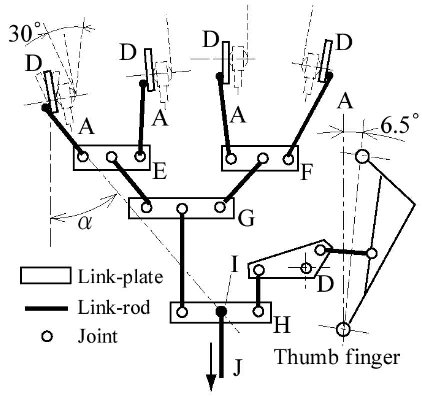

Fig. 8 Link Mechanism

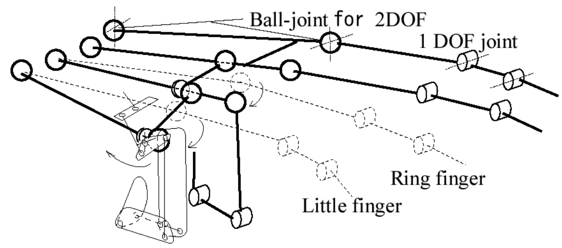

Fig. 9 Movement motion of the Palm part

4.2. Thumb finger

The human thumb is a very complex mechanism. This finger is extremely difficult to model accurately, since it allows multidimensional motion and it is directly tied with the bones of the human hand at the wrist. Therefore, we constructed the thumb finger with a simple structure: it has only one degree of freedom, which is fixed on the basic plate. The rotational axis is set at an angle of 6.5 degrees to the vertical line of the basic plate. We believe this is sufficient in order to grasp many objects because the hand can already grasp a wide variety of objects if the thumb finger only operates to fix the object position as a fulcrum.

4.3. Link mechanism and palm design

Fig. 8 shows the linkage system of the finger motion. The four fingers and the thumb finger are connected with some links by the link-plate E to H and every joint is free movable. By using weak springs or rubber bands, each finger can easily return to its index position.

Each link starts working by itself with the strain of the link-rod A when the link-rod J is pulled. Every finger will be moved because link-rods A pull each finger through the link-plate D. The link-plate E starts a rotation centered on a joint point of the link-rod A of the little finger when the little finger touches the object to be grasped. The link-plate G also starts a rotation centered on a joint point from the link-plate E when the ring finger touches the object, while the index, middle and thumb fingers keep moving. Thus, every link keeps being moved by the link-rod J until every finger touches the object. Therefore, each link moves to keep the balance of the strain force on every link when the contact force of some finger becomes suddenly weak. Finally, the contact force of every finger becomes evenly again. Additionally, the link-plate E affects the metacarpal rods of the little and ring fingers towards the object if the ring and little fingers touch the object (Fig 9). Since the fingers and the palm are capable of evenly touching the object, a more stable and safety grasping and holding of the object can be achieved.

The link-plate E of the index and little fingers is located at an angle α to the link-rod J (Fig. 8). Therefore, both fingers can grasp the object with an adduct force and the object can be touched with the side surface as it would be handled by a human being.

5. Results and comparison

In this section, we first present examples of grasping objects corresponding to the basic types of hand grasping. Fig. 10 shows a picture of the grasping experiments performed by the proposed and designed model of the humanoid hand with the grasping types mentioned above. The objects we use are common objects. These are a glass with coffee, a matchbox, a door handle, a pen, a tennis ball and a triangle. It is evident that every grasp type is sufficiently well holding. We observed only very slight deviations from the human grasping shape. This shows that the link mechanism, the adduction/abduction function of the MP joints and the palm motion ability are effectively working in grasping and holding the objects.

Fig. 10(b) shows a pick up motion of a small object (matchbox). The index finger produces force component towards the center of the object. The thumb finger also produces a force in the direction of the index and middle fingers (i.e. the center of the object) since the rotation axis of the thumb is located at an angle of 6.5 degrees to the vertical line of the basic plate. Therefore the humanoid hand can hold tight because each fingertip pushes at the object.

The little finger is shorter than the other fingers. Accordingly it should be difficult to reach the object with the little finger, for example in the case of a hook grip around a drawer handle. However, human beings generally use also the little finger to open a drawer. Fig. 10(c) shows a hook and pull hand operation. We can easily observe the change of the location of the fingertip and the root of the little finger. Thus, the little finger reacts to many conditions with the action of palm.

We appreciate that extra devices should be employed in order to accomplish the special cases of the Palmar and Lateral grasping types. For instance, it is difficult to execute actions like a pick up operation of a pen and then to change the grip style, because independent movements of every finger are necessary to change the grip style. However, we retain that it is possible to control easily each finger to a certain extent by using simple devices like an electrical brake or an electromagnet pin control on the link-rod of every finger.

6. Conclusions

In this paper we presented the mechanical design concept and experimental results of the TUAT/Karlsruhe humanoid hand. The humanoid robot ARMAR and an artificial arm were also described. The humanoid hand is able to grasp and hold objects with the fingers and the palm by adapting the grip to the shape of the object, through a selfadjustment functionality. The hand is driven by only one actuator. Therefore, it is not necessary to use feedback sensors in the hand because the griping force adjusts the grasp position and the posture of the five fingers. This is greatly useful to simplify the hand control system. As a further result, we confirmed that with the humanoid hand, it is possible to fulfill our demands for typical manipulation tasks of humanoid robots and artificial arms for handicapped people.

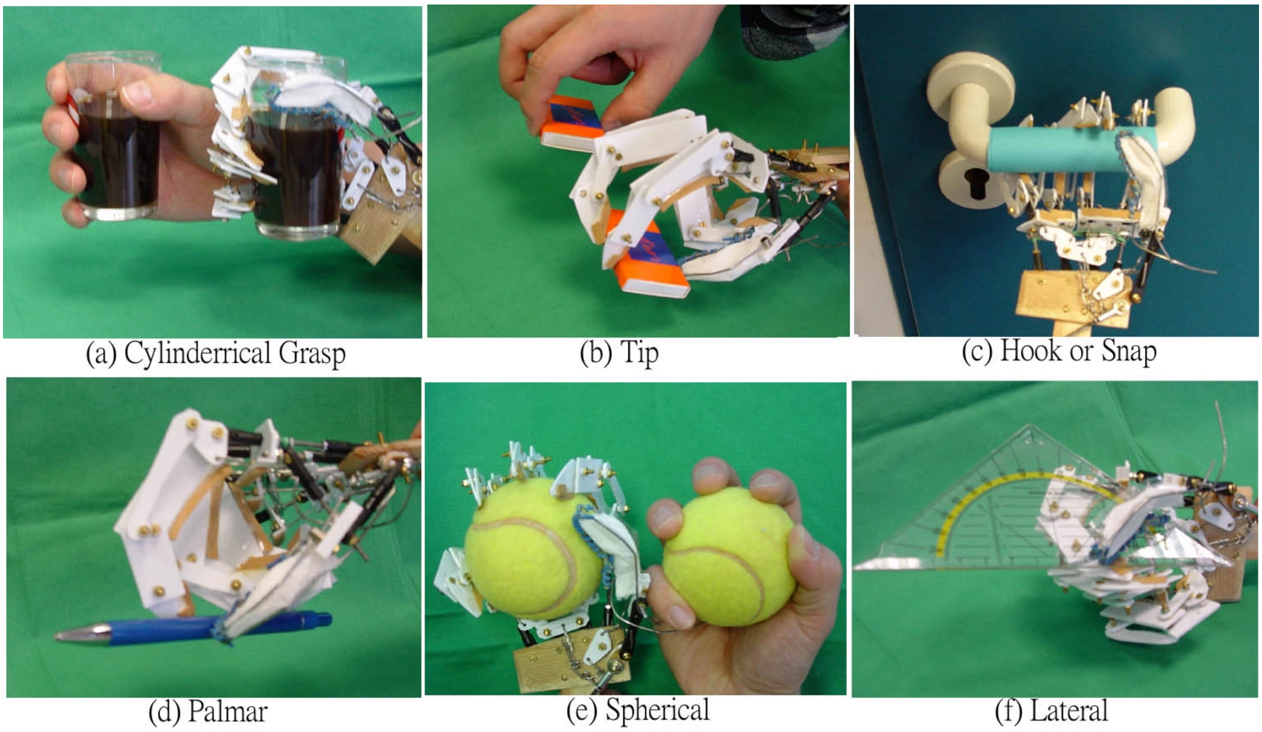

Fig. 10 Grasping examination by the TUAT/Karlsruhe humanoid hand

Acknowledgment

The presented research is supported by the "Encourage the young researcher project" by the Japan Foundation for Aging and Health. Special thanks to the president of the Japan Foundation for Aging and Health Takeshi Nagano, to the staff of the research group of Tokyo University of Agriculture, to the staff of the Institute for Control and Robotics and to the staff of Forschungszentrum Infomatik at the University of Karlsruhe.

References

[1] T. Asfour, K. Berns and R. Dillmann, "The Humanoid Robot ARMAR", Proc. of the Second International Symposium on Humanoid Robots (HURO´99), October 8-9, 1999, Tokyo, Japan

[2] T. Asfour, K. Berns, J. Schelling and R. Dillmann, "Programming of Manipulation Tasks of the Humanoid Robot ARMAR", The 9th International Conference on Advanced Robotics (ICAR'99), 25-27 October, Tokyo, Japan

[3] S. Toyama, S. Hatae and S. Sugitani, "Multi-Degree of spherical ultrasonic motor", Proc. ASME Japan/USA Sympo. Flexible Automation, 169, 1992

[4] N. Fukaya, S. Toyama and T. Seki, "Development of an artificial arm by use of spherical ultrasonic motor", The 29th Int. Sympo. Robotics, Bermingam, England, 74, 1998

[5] S.C.Jacobsen, E.K. Iversen, D.F. Knutti, R.T. Johnson and K.B. Biggers, "Design of the Utah/MIT dexterous hand", Proc. IEEE Int. Conf. On Robotics and Automation, pp. 1520-1532, 1986

[6] M. Rakic, "Mutifingerd Robot Hand with Selfadaptability", Robotics and Computer-Integrated Manufacturing, Vol. 5, No. 2/3, pp. 269-276, 1989

[7] R. M. Crowder, " An anthropomorphic robotic end effect", Robotics and Autonomous Systems, Vol.7, pp. 253-268, 1991

[8] M. Umetsu, N. Afzulpurkar, Y. Kuniyoshi and T. Suehiro, "Implementation of a distributed controller for the RWC dexterous hand", Robotics and Autonomous Systems, Vol.18, pp. 13-19, 1996

[9] G. A. Bekey, H.Liu, R. Tomovic and W. J. Karplus, "Knowledge-Based control of grasping in robot hands using heuristics from human motor skills", IEEE Transctions on Robotics and Automation, Vol. 9, No. 6, December, pp. 709-722, 1993

[10] A. Meghdari, M. Arefi, and M. Mahmoudian, "Geometric Adaptability: A Novel Mechanical Design in The Sharif Artificial Hand", Biomechanics Sympo. ASME, AMD-Vol. 120, pp. 219-223, 1991

[11] H. Ito, "*Tsukamite no dousa kinou kaiseki*", Biomechanism, Vol.3, pp. 145-154, 1975 (in Japanese)

[12] A. D. Keller, C. L. Taylor and V. Zahm, "Studies to determine the functional requirements for hand & arm prostheses", Dept. of Engr., UCLA., CA, 1947

[13] Kapandiji, I., "The Physiology of joints", Churchill Livingstone, NY, USA, 1970