Int J Soc Robot
DOI 10.1007/s12369-011-0106-y

GCUA Humanoid Robotic Hand with Tendon Mechanisms and Its Upper Limb

Demeng Che · Wenzeng Zhang

Accepted: 2 September 2011

Abstract Upper limbs of human beings are extremely special and significant, which obtain crucial function to achieve manipulations intelligently and dexterously. Gesture-Changeable Under-Actuated (GCUA) grasping function is presented to improve the capability of robotic hands to achieve humanoid manipulations with low dependence on control and sensor feedback systems, which includes traditional under-actuated (UA) grasping motion and special pre-bending (PB) motion. Based on GCUA function, GCUA Hand II is developed, which has 5 fingers and 14 DOF. All the fingers use similar tendon mechanisms and motors to achieve GCUA function. With GCUA Hand II, a humanoid robot upper limb system is designed, which has two 3-DOF arms actuated by stepper motors and two 14-DOF hands actuated by DC motors. The control system includes four parts: a computer, a FPGA motion controller, a driver module, and a user module, which can control the upper limb system to do various movements dexterously and exactly. With C++ language, a spatial motion program is designed to assist researchers to determine spatial motions of the upper limb system. This system has a great prospect in the field of rehabilitation engineering, extremely environmental manipulation, humanoid robotics and social services.

Keywords Humanoid robot · Robot hand · Upper limb · Self-adaptation · Gesture-changeable under-actuated function

D. Che · W. Zhang (✉)
Dept. of Mechanical Engineering, Tsinghua University, Beijing 10008, China
e-mail: wenzeng@tsinghua.edu.cn

D. Che
e-mail: demeng.che@gmail.com

1 Introduction

Since 1960s, when Devol and Engelberger created the first industrial robot: Unimate [1], manipulators have undertaken many rough and dangerous tasks for people in the field of industrial manufacturing, such as welding, painting, assembly, product inspection and testing.

The Second Chinese Sample Survey of Disability shows that there are more than 24.12 million citizens with physical disabilities [2], which led robot researchers and designers to take interest in humanoid upper limb systems with dexterous robotic hands which can give excellent humanoid performance and assist disabled people to achieve daily activities. Most industrial robots use grippers or tools as their terminals to grasp and manipulate objects. However, humanoid robots need upper limbs with artificial multi-fingered hands, which are expected to achieve typical human tasks in unstructured environments [3]. Combining manipulators and dexterous hands, modern humanoid robot upper limbs are designed to achieve humanoid manipulations. For instance, A.M. Dollar designed four-fingered, under-actuated SDM (Shape-Deposition-Manufacturing) hand mounted on a whole-arm manipulator [4].

In modern times, the study on robot upper limb system promotes the development of power-assisted rehabilitation. The orthosis works by maintaining arm positions and power assisting motions for the patients who wear the rehabilitation upper limbs [5]. On the other hand, the design of robot upper limb system allows the implementation of sophisticated control algorithms and manipulation behaviors and the study of mobile manipulation and strategies of service robotics [6]. In the nearly fifty decades, as a branch of robot upper limb system, exoskeletons for upper limbs have progressed from the stuff of science fiction to nearly commercialized products [7], which are supposed to play an cru-

Published online: 28 September 2011

cial role in the field of rehabilitation, motion assist, human power augmentation and haptic interaction [8].

There are plenty of achievements in the field of robot upper limb system. German Aerospace Center (DLR) designed "Rollin's Justin", a multi-DOF mobile robotic system with two arms and two DLR dexterous hands which has an anthropomorphic kinematic configuration for research on bimanual grasping [9]. The robot uses telepresence system to enable human operators to explore a remote environment [10]. Sarcos Inc. designed a seven DOF hydraulically actuated exoskeleton robot arm: Sarcos Master Arm to mimics the major seven DOF of the human arm [11]. J.C. Perry developed an anthropometric seven-DOF powered exoskeleton for human upper limb which can be used as a therapeutic and diagnostics device for physiotherapy [12].

As the terminal of humanoid robot upper limb, anthropomorphic robot hands, including dexterous hands and under-actuated hands, are taken into account. Since J.K. Salisbury showed first in 1980s that the minimum number of DOF to achieve dexterous manipulation in a hand with rigid finger and non-sliding contacts in manipulation theory is nine [13, 14]. In general, dexterous hands use more than 9 actuators to drive joints to achieve dexterity in manipulation.

In the early 1980s, The Center of Engineering Design, University of Utah, and the Artificial Intelligence Lab, MIT, designed a dexterous robotic hand: UTAH/MIT Hand, which promotes the experimental research of basic concepts in manipulation theory, tactile sensing and control system [15].

M.A. Saliba has designed a compact and dexterous robot hand [16]. All actuators and sensors of the hand are located remotely from the fingers, which makes the hand small enough. The MP joint and the PIP joint of each finger are driven by an actuator respectively, and the cable and pulley coupling mechanism between the PIP joint and the DIP joint makes these two joints rotate synchronously. The hand can achieve a lot of humanoid motions dexterously.

I. Yamano used ultrasonic motors and elastic elements to develop a 5-fingered robot hand [17]. The index, middle, ring and little fingers use three ultrasonic motors to drive four joints respectively, and the thumb uses three ultrasonic motors to drive three joints. The hand with twenty joints can perform stable and compliant humanoid grasping motions.

W. Zhang designed a humanoid robot hand: GCUA Hand, which has 5 fingers and 15 DOF [18, 19]. Based on a novel grasping function: gesture-changeable under-actuated (GCUA) function, the hand can grasp different objects self-adaptively and do many humanoid gestures.

SKKU Hand II with a finger-tip tactile sensor was designed by B. Choi [20], which has a thumb and three fingers. The thumb has 4 joints with 4 DOF, and each finger has 3 joints with 2 DOF. Moreover, the finger-tip tactile sensor is flexible enough to feel 3-dimensional forces.

N. Tsujiuchi designed balloon-type pneumatic actuators, and used those actuators to develop a 5-fingered robot hand. The hand has a movable range similar to a human being's hand, which can hold a variety of objects [21].

In order to replicate humanoid social touch, J.J. Cabibihan [22] compares the skin's characteristics such as compliance, conformance and hysteresis among common robotic skin materials, include silicone and polyurethane, with the human finger behavior.

Recently, some important achievements have obtained in expressing human-like emotions by a emotion expression humanoid robot WE-4R (Waseda Eye No. 4 Refined) with five-fingered robotic hands, named RCH-1 (Robocasa Hand No. 1) [23]. The design aim of the system includes grasping and expression of emotions through hand gestures.

Section 2 reviews our previous Gesture-Changeable Under-Actuated function which includes two main motions: under-actuated (UA) motion and pre-bending (PB) motion, and shows the advantages of the action principle of GCUA Hand II. Section 3 presents the development of a new multi-fingered hand which uses tendon mechanisms and elastic elements to achieve GCUA function. Section 4 gives the development of the novel humanoid robot upper limb system with special emphasis on mechanical design features, control issues and algorithms design. Section 5 presents experimental results of the upper limb system to illustrate and validate our design.

2 Action Principle of GCUA Hand II

An under-actuated (UA) robot hand is a hand which has a lower number of actuators than degrees of freedom [24]. Under-actuation can provide UA hands a significant grasping function called self-adaptive grasping which means that UA hands can grasp various objects with different shapes and sizes self-adaptively. For instance, TH-3 hand designed by Tsinghua University [25] is a typical self-adaptive UA hand, each finger of which can use only an actuator to drive two or three DOF. TH-3 hand can use under-actuated function to grasp objects in this way: when its motors actuate MP joints to rotate forward, PIP and DIP joints feel hard to rotate with the constraint of the returning spring; when proximal and middle phalanges are blocked by objects, PIP and DIP joints can rotate respectively.

Another possible way is to design specific mechanisms so that joints can bend or flex in order. An example of this kind of UA hand is a multi-function mechanical hand with shape adaptation which was designed by G. Guo [26]. The hand exploits linkage and gear transmission to achieve shape adaptation grasping. However, gear transmission makes PIP and DIP joints rotate together in specific angle proportion, which makes the hand feel hard to meet the requirements of

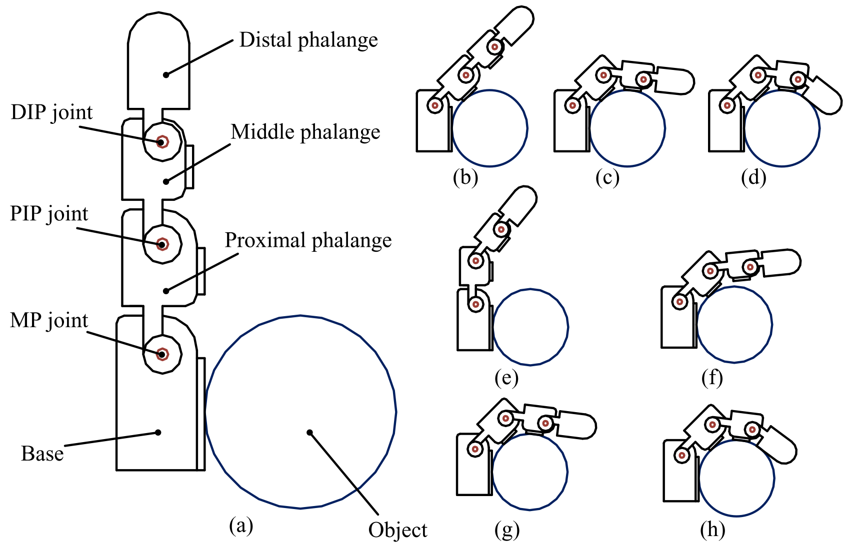


Fig. 1 Action principle of GCUA Hand II finger with 3 joints. (**a**) Initial gesture (keep straight); (**b**) MP joint keeps rotating until proximal phalange touches the object; (**c**) PIP joint keeps rotating until middle phalange touches the object; (**d**) DIP joint keeps rotating until distal phalange touches the object; (**e**) PIP joint keeps rotating to change the finger's initial gesture; (**a**, **b**, **c**, **d**) UA motion; (**a**, **e**) PB motion; (**f**, **g**, **h**) UA motion with the changed initial gesture

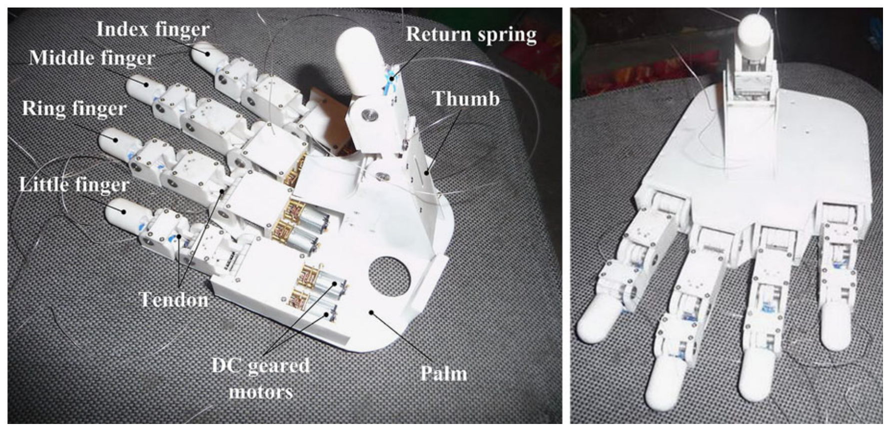


Fig. 2 GCUA Hand II

dexterous humanoid movements, such as joints rotation with various angles in different time.

Gesture-Changeable Under-Actuated (GCUA) function is presented to overcome the weak points of the above UA hands. The paper designs a GCUA Hand II with GCUA function to give humanoid manipulations. GCUA function includes two main motions: under-actuated (UA) motion and pre-bending (PB) motion, which is shown in Fig. 1. On the one hand, the hand can use UA motion to give humanoid self-adaptive grasping on various objects. In fact, self-adaptive grasping function plays an important role to makes robot hands less dependent on senor and control system, which makes GCUA Hand II easy to control than dexterous hands with numerous active DOF. On the other hand, the robot hand can change its initial gesture (the gesture before touching objects) with PB motion. Therefore the hand feels easy to achieve various humanoid poses, like pinching and typing. In a word, the combination of UA motion and PB motion makes the hand easy to achieve humanoid manipulations dexterously and stably.

3 Mechanical Design of GCUA Hand II

The GCUA Hand II, such as shown in Fig. 2, has four fingers and a thumb with 14 DOF (10 active DOF and 4 under-actuated DOF). All the fingers and thumb are embedded in the palm, whose sizes are similar with human being's. Thumb has a 60 mm length; forefinger has an 87.5 mm length; middle finger has a 90.5 mm length; ring finger has an 84.5 mm length; litter finger has a 75.5 mm length. The anthropomorphic mechanical design makes GCUA Hand II perform excellent power grasping and many other humanoid manipulations.

In this section, the design of the finger module is presented firstly, each of which has three joints to connect three phalanges and the base; secondly, the paper gives the design of the thumb module which has two joints to connect two phalanges and the base; the design of the motor drive board is given at last. The design of these three main modules of GCUA Hand II makes GCUA Hand II feel easy to manufacture and maintain.

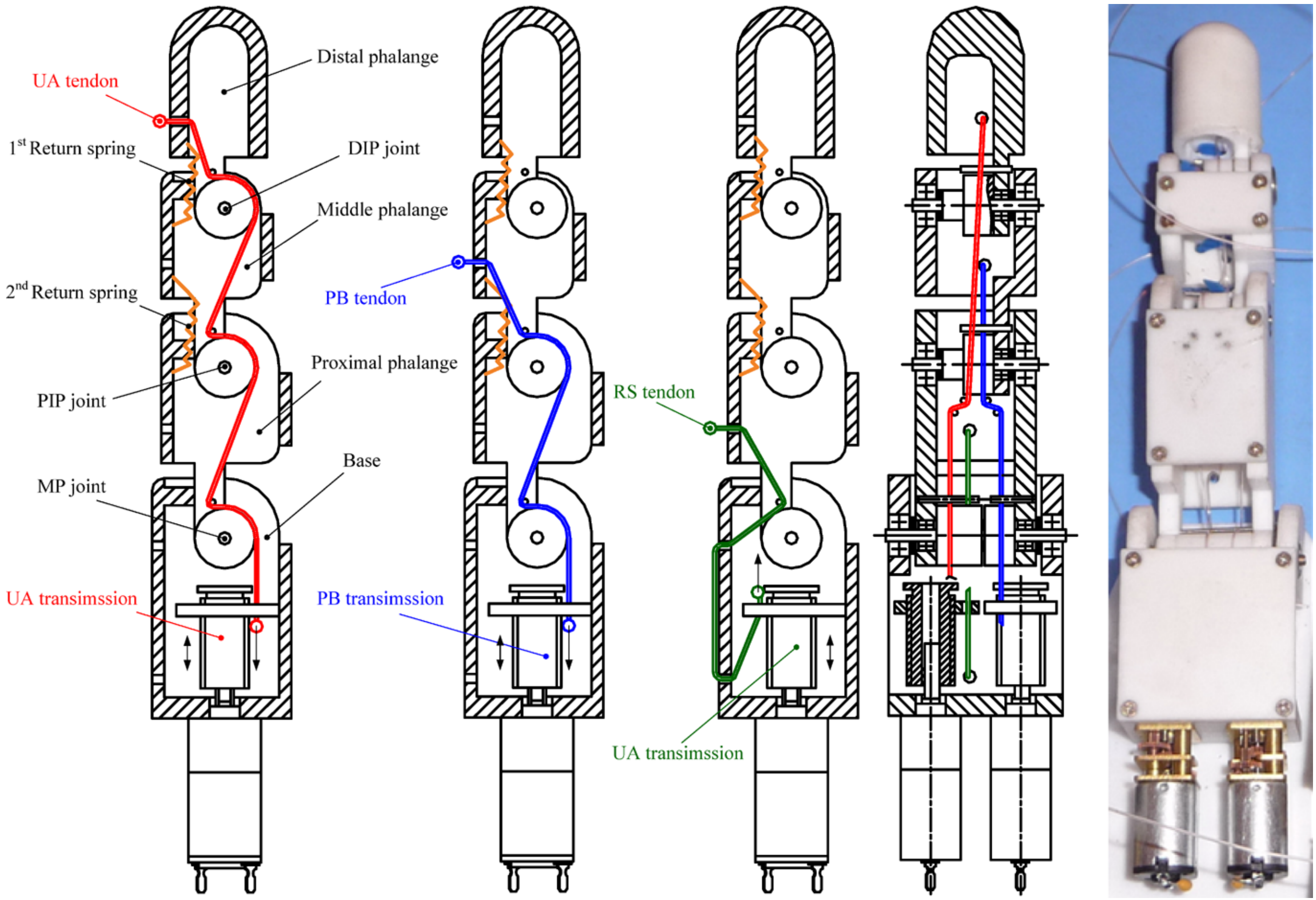


Fig. 3 Finger module. (**a**) Assembly method of UA tendon; (**b**) Assembly method of PB tendon; (**c**) Assembly method of RS tendon; (**d**) Front cutaway view; (**e**) Finger module

3.1 Finger Module

Four fingers of GCUA Hand II are index finger, middle finger, ring finger and little finger, the structure of which is shown in Fig. 3.

Finger module has three joints and three phalanges. MP joint is located in base to connect base and proximal phalange; PIP joint is located in proximal phalange to connect proximal and middle phalange; similarly DIP joint is located in middle phalange to connect middle and distal phalange. UA transmission and PB transmission are both embedded in base, which are driven by tendons to achieve UA motion and PB motion respectively. The 1st return spring combines middle phalange and distal phalange, the 2nd return spring combines proximal phalange and middle phalange. All the joints of the finger module can bend and flex dexterously with three tendons: under-actuated (UA) tendon, restrictive (RS) tendon and pre-bending (PB) tendon.

Figure 4 shows the grasping process of UA motion. Firstly, the 1st motor rotates forward to drive UA transmission to pull UA and RS tendons so that these two tendons will move down. Since the reverse wrapping directions of

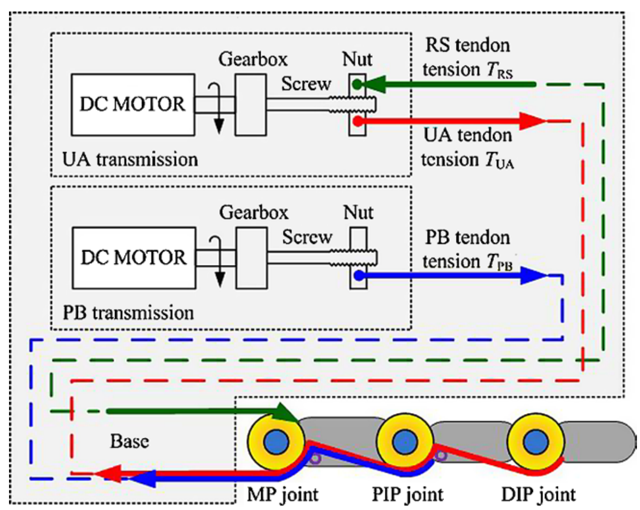


Fig. 4 Conceptual sketch map of UA motion and PB motion of the finger module

UA and RS tendons makes UA tendon tension and RS tendon relax, UA tendon will pull distal phalange to rotate. The 1st and the 2nd return springs makes proximal, middle and

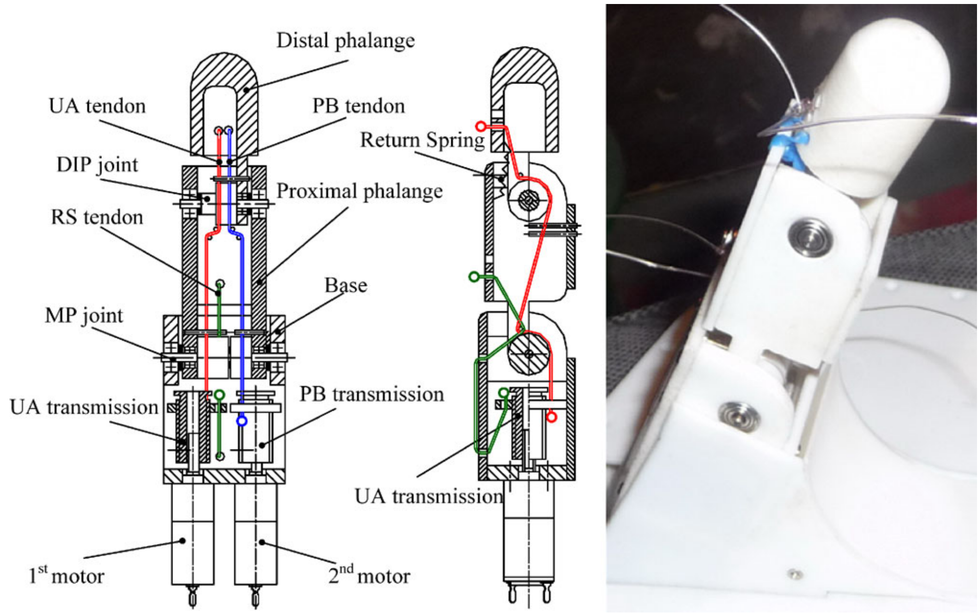


Fig. 5 Thumb module. (**a**) Front cutaway view; (**b**) Side cutaway view; (**c**) Thumb module

distal phalanges rotate around proximal joint together as a rigid body. When proximal phalange is blocked, the other two ones will rotate together around middle joint and the 2nd return spring will be deformed; similarly, when middle phalange is blocked, distal phalange will rotate around distal joint and the 1st return spring will be deformed. In this way, the finger module can grasp various objects self-adaptively.

The process of PB motion is also shown in Fig. 4. When the finger module wants to achieve PB motion, the 2nd motion rotates forward to drive PB transmission to pull PB tendon so that the finger module can change its initial gesture. The reverse wrapping directions of RS and PB tendons and the constraint of the 1st return spring makes middle and distal phalanges rotate together to change its initial gesture.

3.2 Thumb Module

GCUA Hand II has a thumb which is shown in Fig. 5. The two actuators of the thumb module drive 2 active DOF to rotate. MP joint is located in base to connect base and proximal; similarly DIP.

DIP joint is fixed in proximal phalange to connect proximal and distal phalanges. UA transmission and PB transmission are both embedded in base. Proximal phalange is fixed around MP joint and distal phalange is fixed around DIP joint. Return spring combines proximal phalange and distal phalange.

The design of the thumb module's structure and action principle is similar to the finger module. The modular design of the hand makes it easy to manufacture and assemble.

3.3 Motor Driver Board

GCUA Hand II has five motor driver boards which are placed on the palm. As it is shown in Fig. 6, each board has a length: 40.5 mm and a width: 30.0 mm. With a L293D driver IC as the control center, each driver board can be directed by PWM signals and drive two DC motors to run towards different directions with various rotate speeds.

4 Humanoid Robot Upper Limb System

The humanoid robot upper limb system, such as shown in Fig. 7, has two 3-DOF robot arms and two 14-DOF GCUA Hand II. The length of each arm is 436 mm including a 206 mm upper arm and a 230 mm forearm. 3-FOD arms ensure the upper limb system to reach certain points in a large space; moreover, GCUA Hand II enables the upper limb system to give dexterous humanoid manipulations. This section presents the mechanical design, control system and spatial motion program of the upper limb system.

4.1 Three-Joint Robot Arm

The 3 DOF arm includes upper arm and forearm. Three joints of the arm are the 1st, the 2nd and the elbow joint. The arm is driven by three stepper motors so that its three joints can rotate certain angles in required rotational speed. The design of the robot arm is shown in Fig. 8. The hollow shaft of each joint makes it easy set control and power wires through the whole arm; simultaneously the design of the hollow shaft can improve the movement stability of the arm. According to geometrical analysis on the motion of three

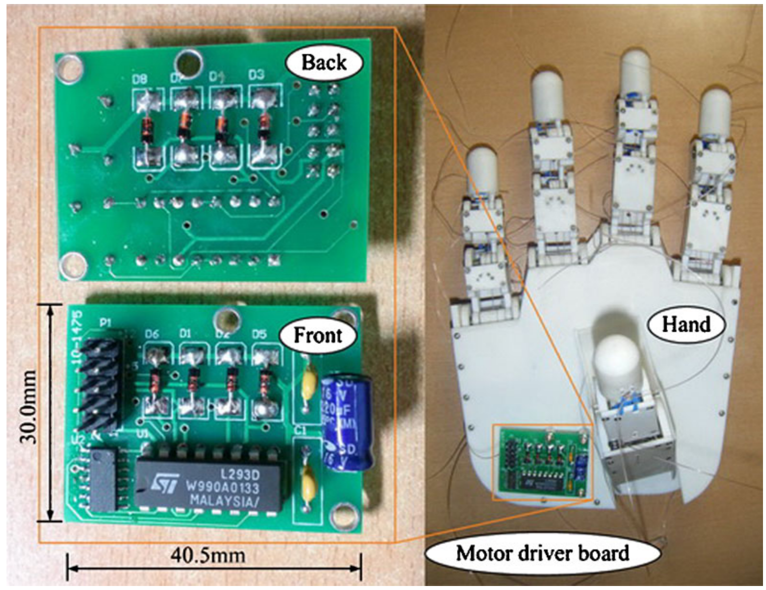


Fig. 6 Motor driver board

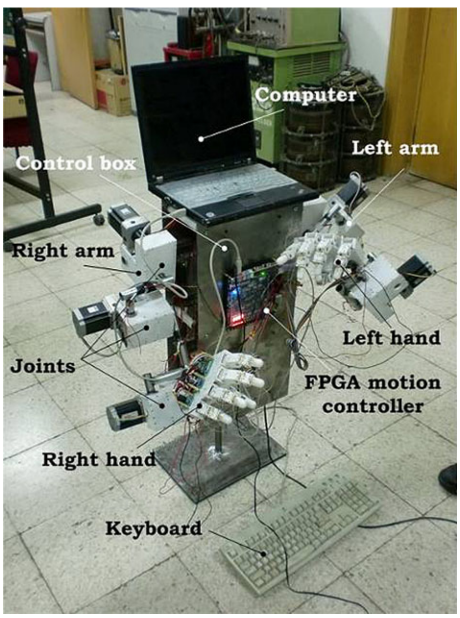


Fig. 7 Structure of the humanoid robot upper limb system with GCUA Hand II

joints, the terminal of the upper limb system can reach any point in a spherical shell with a 146 mm internal diameter and a 970 mm external diameter.

4.2 Control System

The four parts of the control system are computer, FPGA motion controller, driver module and user module. Driver module includes DC motor driver boards and stepper motor drivers; user module includes three-joint robot arm and GCUA Hand II.

Using VHDL to program, the computer can communicate with FPGA motion controller through USB bus and enable FPGA motion controller to create required PWM signals in certain I/O ports. Directed by the PWM signals which are created by FPGA motion controller, user module can achieve its motion function through driver module. The whole control diagram of the humanoid robot upper limb system is presented in Fig. 9.

4.3 Spatial Motion Program

A spatial motion program is developed, based on C++ language, to assist researchers to compute and design specific space motions for the humanoid robot upper limb system.

The spatial motion program, such as shown in Fig. 10, can save the data of the rectangular coordinates of the given points at first. Afterwards the program can transform the data of rectangular coordinates to the date of joint coordinates based on various mechanical data, and then assist researchers to work out the required number of pulse signals which will be given into each stepper motor driver to ensure certain rotation angles of each stepper motor.

The following paragraphs propose the algorithm for coordinate transformation. Firstly, only consider the spatial motion of the robot upper limb on a two-dimensional plane, which is shown in Fig. 11. Considering the geometrical relationship, the following equations can be obtained,

$$x = r_1 \cos\theta_1 + r_2 \cos(\theta_1 + \theta_2), \tag{1}$$

$$y = r_1 \sin\theta_1 + r_2 \sin(\theta_1 + \theta_2) \tag{2}$$

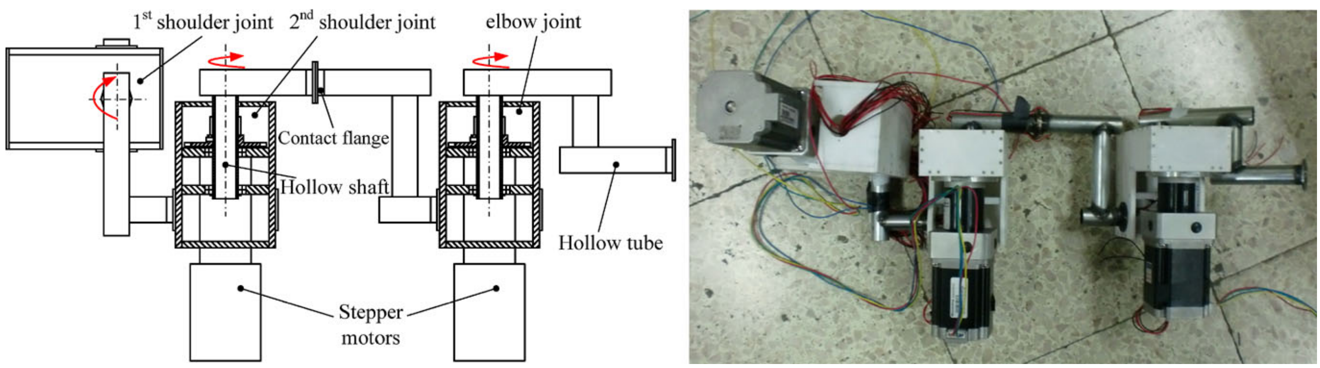
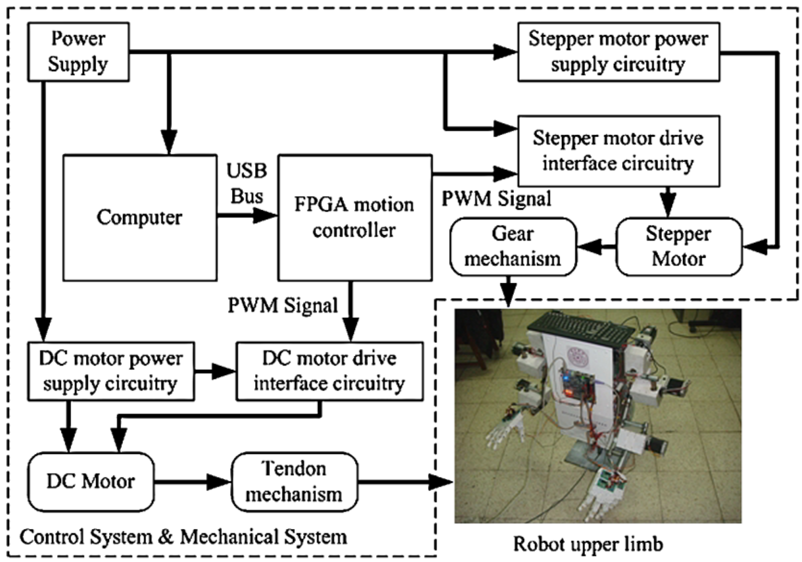


Fig. 8 Structure of three-joint robot arm. (**a**) Front cutaway view; (**b**) Three-joint robot arm

Fig. 9 Overall control diagram of the humanoid robot upper limb system



Combining (1) and (2), θ_2 and the relationship between θ_1 and θ_2 can be obtained as follows,

$$\theta_2 = \cos \frac{y^2 + x^2 - r_1^2 - r_2^2}{2r_1 r_2}, \tag{3}$$

$$\begin{bmatrix} r_1 + r_2\cos\theta_2 & r_2\sin\theta_2 \\ -r_2\sin\theta_2 & r_1 + r_2\cos\theta_2 \end{bmatrix} \begin{bmatrix} \sin\theta_1 \\ \cos\theta_1 \end{bmatrix} = \begin{bmatrix} y \\ x \end{bmatrix} \tag{4}$$

Considering (4), the following equation can be obtained,

$$\theta_1 = \arccos \frac{(r_1 + r_2\cos\theta_2)x + r_2\sin\theta_2 y}{(r_1 + r_2\cos\theta_2)^2 + r_2^2\sin^2\theta_2} \tag{5}$$

The rectangular coordinates of points can be transformed to joint coordinates by combining (3) and (5). Subsequently, consider the problem of the spatial motion on a three-dimensional space, which is shown in Fig. 12. Based on geometrical relationship, θ_3, x' and y' can be obtained as follows,

$$\theta_3 = \arctan(z/x), \tag{6}$$

$$x' = x/\cos\theta_3, \tag{7}$$

$$y' = y \tag{8}$$

Combining (3), (5), (7) and (8), the following equations can be obtained,

$$\theta_1 = \arccos \frac{(r_1 + r_2\cos\theta_2)x' + r_2\sin\theta_2 y'}{(r_1 + r_2\cos\theta_2)^2 + r_2^2\sin^2\theta_2} \tag{9}$$

$$\theta_2 = \cos \frac{(y')^2 + (x')^2 - r_1^2 - r_2^2}{2r_1 r_2} \tag{10}$$

Based on (6), (9) and (10), the motion program can feel easy to transform rectangular coordinates of points to joint coordinates efficiently. Subsequently, the required number of pulse signals which will be given into each stepper motor driver can easily be solved out.

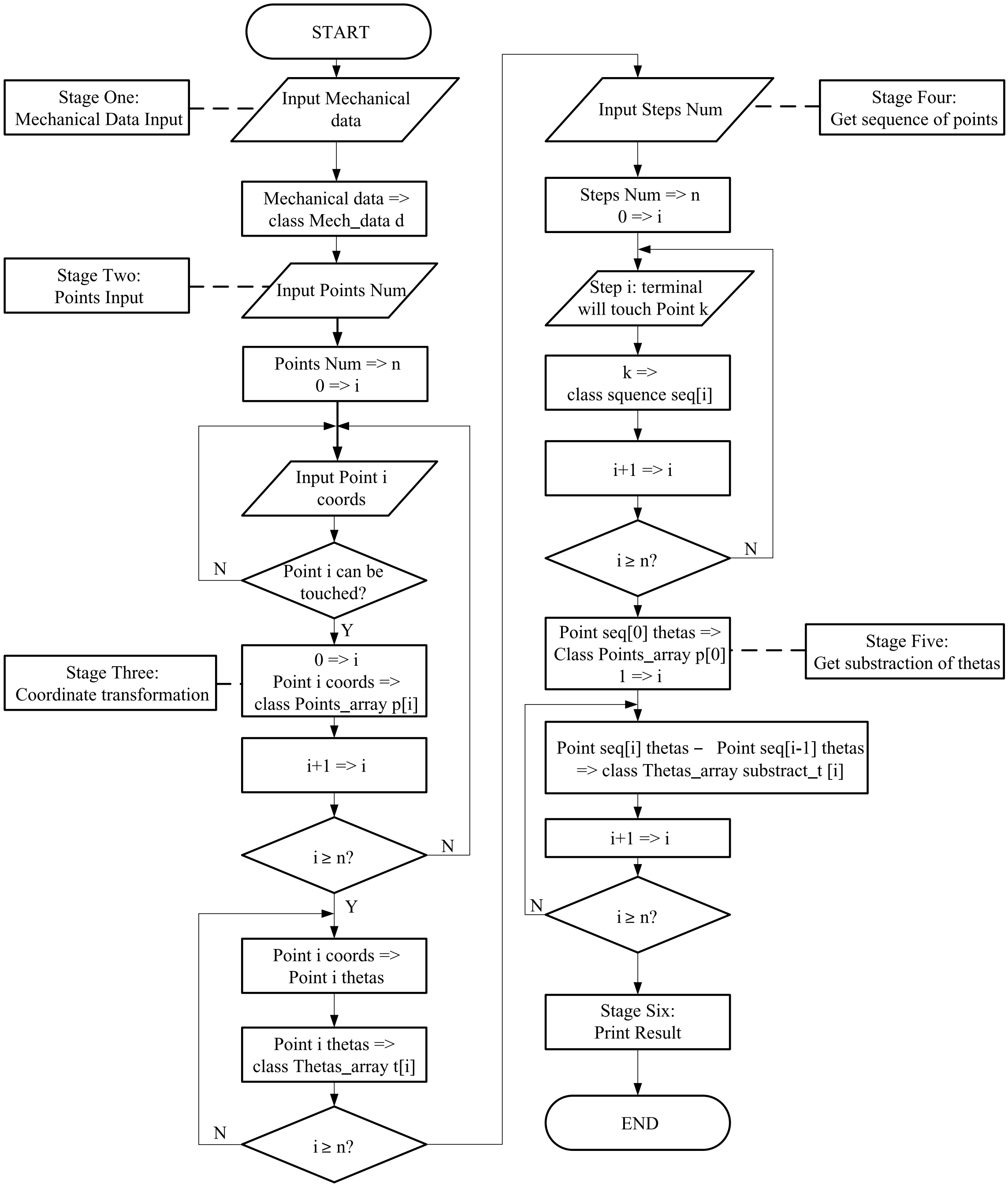


Fig. 10 Flow chart of spatial motion program

5 Grasping and Motion Experiments

Some grasping experiments of GCUA Hand II are presented in Fig. 13. Traditional under-actuated hand can only use UA motion to grasp objects, that's why it must choose a good position to grasp specific objects, like pen, for example, the hand will feel easy to only rotate MP joint to grasp a pen with fingertips. Similarly, GCUA hand can also only use UA motion to perform humanoid self-adaptive grasping on various objects, such as pen, cube or cylinder; moreover, the cooperation of UA motion and PB motion enables the hand to rotate MP joint and PIP joint to perform more human-like motions and do certain humanoid operation like pressing buttons, holding a pen, and so on. The humanoid robot upper limb system, such as shown in Fig. 14, can grasp a baseball stably with a nice human-like performance.

6 Conclusion

The paper reviews our previous gesture-changeable under-actuated (GCUA) function including two main motions: under-actuated (UA) motion and pre-bending (PB) motion. Based on GCUA function, GCUA Hand II is designed which utilizes PB motion to change its initial gesture and gives humanoid self-adaptive manipulations with UA motion. The paper presents the development of a novel humanoid robotic upper limb system with GCUA Hand II. The system can achieve various human-like movements and manipulations dexterously and efficiently. Moreover, the design of GCUA upper limb control system and spatial motion program are given. This system can be used as a potential application in the field of rehabilitation engineering, extremely environmental manipulation, humanoid robotics and social services.

Acknowledgements This paper was funded by National Natural Science Foundation of China (No. 50905093).

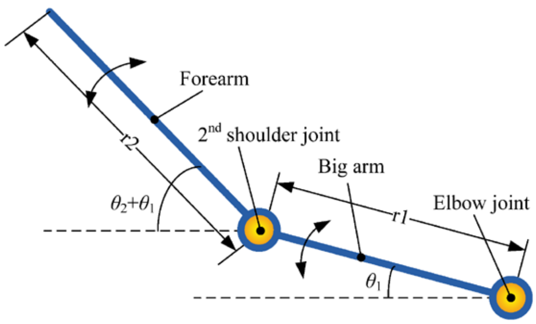


Fig. 11 Sketch map of the arm with 2 joints

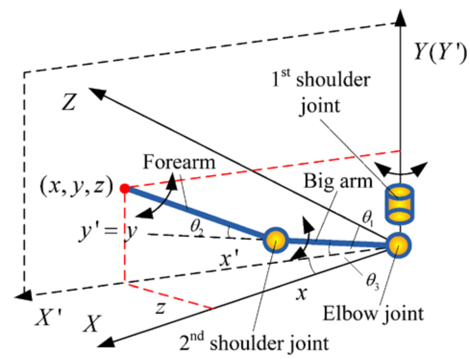
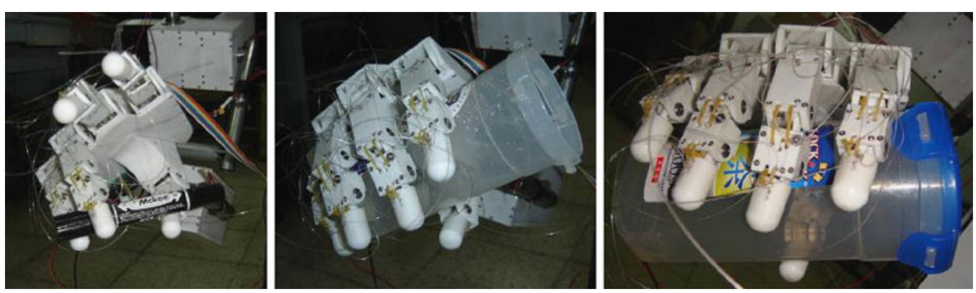


Fig. 12 Sketch map of the arm with 3 joints



(a) (b) (c)

Fig. 13 Some humanoid grasping movements of GCUA Hand II. (**a**) Hold a pen; (**b**) Grasp a cup (cylinder); (**c**) Grasp a cup (cube)

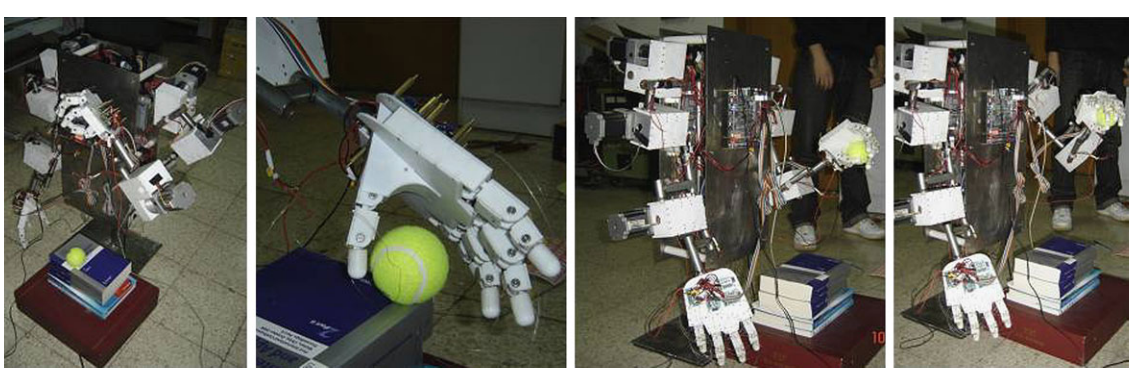


Fig. 14 The humanoid robot upper limb system grasps a baseball

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Demeng Che born in 1988, is currently an undergraduate student in the Department of Mechanical Engineering, Tsinghua University, China. His research interests include anthropomorphic robot hand and humanoid robot. He is a recipient of National Research Innovation Program for University Students sponsored by Ministry of Education of the People's Republic of China. He received the Best Paper Award of an international conference.

Wenzeng Zhang born in 1975, is currently an associate professor in the Department of Mechanical Engineering, Tsinghua University, China. He received his B.S., M.S. and Ph.D. degrees from Tsinghua University, China, in 1999, 2002, 2005. His research interests are in the areas of humanoid robotics, underactuated robot hand, and visual servoing. He has over 90 publications. He received six Best Paper Awards at international conferences on robotics (ICFDM2004, ICFDM2010, ICIRA2008, ICIRA2009, ICSR2010, RWIA2010). He obtained more than 50 Chinese invention patents. He has received a number of educational awards from his university.