ROBOMECH Journal
a SpringerOpen Journal

REVIEW

CrossMark

On the development of intrinsically-actuated, multisensory dexterous robotic hands

Hong Liu, Dapeng Yang[*], Shaowei Fan and Hegao Cai

Abstract

Restoring human hand function by mechatronic means is very challenging in robotics research. In this paper, we first make a brief review on the development of dexterous robotic/prosthetic hands, and then detail our design philosophy of several robot hands. We make a concentration on a type of intrinsically-actuated robot hands, wherein the driving, transmission, and control elements are totally embedded in the hand. According to different application scenarios, we develop robot hands in two parallel lines, dexterous robotic hand and anthropomorphic prosthetic hand. In both, the hand's actuation, sensing, and control subsystems are highly integrated and modularized. This feature endows our robot hands with compact appearances, simple integration, and large flexibilities. At last, we give some perspectives on the future development of dexterous hands from the aspects of structure, functionality, and control strategies.

Keywords: Robotic hand, Prosthetic hand, Intrinsic actuation, Modular design

Background

As a powerful tool, a large variety of robotic systems has been applied to help human beings explore unknown or hazardous areas such as outer space, deep sea, or contaminated nuclear plants. To achieve effective explorations, a dexterous end-effector with superior operation and perception capabilities is an urgent need. Although traditional grippers can deal with some simple, fixed tasks (grasping and transferring workpieces), their low commonality, humble perception and insufficient flexibility make them hardly competent to complex operations in unstructured environment. Then, dexterous robotic hands (DRHs) with multiple degrees of freedom (DOFs), superior operational and perceptional capabilities arouse great attentions in the robot society [1]. Currently, although a large progress has been made, the DRHs available on the market still cannot compete to biological hands due to current technical constraints

on actuators, sensors and control means. It is indicated that, rather than simply imitating the human hand, the research should switch to fully exploiting the robot hand's advantages, while considering specific requirements (manipulative dexterity, grasp robustness, or human operability) that allow for successful, fluent, and dexterous operations [2].

As a branch of robotic hand research, the anthropomorphic prosthetic hand (APH) is a type of biomechatronic device used to restore hand motions for amputees or paralyzed patients. On this topic, great efforts have been made from both robotics and biomedical engineering. However, current prosthetic hands still cannot compete to a human hand in respect of structure, sensing, and control strategy. Only a few of prosthesis products can obtain their commercial success. Because of unintuitive control feelings, lack of sensory feedback, and poor hand functionality [3], a large portion of users often refuse to use their prosthesis. After analyzing human hand's activities of daily life (ADL's), a study reveals that a superior hand prosthesis should have more controllable functions, faster response/shorter reaction time, and an intuitive control and feedback strategy [4].

*Correspondence: yangdapeng@hit.edu.cn
State Key Laboratory of Robotics and System, Harbin Institute of Technology, HIT Science Park, No.2 Yikuang Street, Nangang District, P.O. Box 3039, 150080 Harbin, People's Republic of China

Liu *et al. Robomech J* (2016) 3:4

Page 2 of 9

The advanced prosthetic hand systems are then characterized by its anthropomorphic appearance, congenital dexterity (including both mechanical structure and sensors), and high-level mechatronic integration. As for the hand's manipulation capability, it is normally held that the hand dexterity improves as the number of active joints increases. However, studies also shows that, as the number of the active joints increases, the dexterity of a prosthetic hand may even decrease due to the intensified control complexity. Therefore, the prosthetic hand design should consider more comprehensive factors, such as the compromise between dexterity and controllability, the suitability and adaptability of the sensory feedback, as well as essential neural rehabilitation principles [5].

After briefly reviewing some representative studies, in this paper, we detail our development process of several DRH and APH prototypes. From a view of biomechatronics, we also prospect some directions on the development of advanced robot hands, after fully acknowledging the challenges in front of us.

Representative studies

So far, over hundreds of robot hands, including DRHs and APHs, have been developed in academic colleges, research institutions and companies. Among these hands, the DRH is a special topic aiming to reproduce human hand's manipulation dexterity by mechatronic means. According to drive position (inside or outside the hand), the DRH can be mainly divided into two categories: intrinsic actuation pattern (IAP) or extrinsic actuation pattern (EAP). Some representative DRHs with specifications of number of fingers, number of active DOFs, actuation configuration, and transmission mechanism are shown in Table 1.

The design of robotic hands on the early stage, such as Stanford/JPL Hand and Utah/MIT Hand, are generally focused on the hand's anthropomorphism and multi-sensory integration. The DLR-I Hand [7] is a representative of the first generation DRH featured with independent actuation. To enhance the hand's appearance and operating flexibility, the DLR-II Hand [8] further introduces an extra DOF between the thumb and the ring finger for offering palm curling. Driven by air muscles, the shadow hand has more than 20 DOFs that endows the hand with noticeable grasp functions. Besides pure IAP and EAP, many DRHs (such as the iCub hand [15]) also adopt a hybrid driven pattern, wherein multimodal sensors (tactile, position, and force) are also integrated for providing more proprioception information.

Some DRHs are developed for special space and military applications, such as the NASA's Robonaut Hand I, II, and the DLR's Dexhand. Nowadays, the Robonaut hand II has been tested successful in the International

Space Station (ISS) to assist astronaut. Meanwhile, the Dexhand also has some special design, such as its transmission system (Dyneema tendon plus harmonic reducer), control system (totally integrated into the hand), and communication system (CAN Bus and VxWorks controller), for properly working in the space environment. In addition, the DLR's HASy Hand is a new type multi-finger DRH to be used in the bionic Hand-Arm system [10]. It has a similar size, weight, and even behavior to a human hand. To reproduce the dynamic characteristic of the human hand, joints of the DLR HASy Hand are integrated with a special variable stiffness actuation system (VSA, consisting of servo modules and elastic elements) [33]. All actuation and electronic systems are embedded in the forearm, making it easy to be integrated in any concrete applications.

Together with DRH, the development of APH also gets a large promotion. During the last decades of 20th century, many multi-DOF prosthetic hands come into being, such as, Southampton prosthetic hand [34], Oxford Intelligent prosthetic hand [35], Stanford prosthetic hand [36], and NTU prosthetic hand [37]. Due to the actuation techniques and manufacturing level at that time, these prosthetic hands are generally large, heavy, and provided with very limited number of sensors. Upon entering 21st century, the development of APH shows a diverse tendency where the design guidelines are no longer simply "reforming" an existing DRH or totally "reproducing" the human hand. Both scope and depth of interdisciplinary fusion with relevant to mechanic, electronic, biology and control are getting strengthened in the APH development. Today, an ideal APH should possess a human-like appearance, as well as high-level dexterity. As well, it should be comfortable to wear and, more importantly, easy to control. We list a collection of representative APH prototypes, as Table 2 shows.

In particular, the DARPA extrinsic hand adopts a special actuation mechanism named Cobot [49]. It consists of one power motor and 15 steering motors that is able to output 15 channels of motions. According to specific needs, the continuously variable transmission (CVT) device (including operating motor, position sensor, power transmitting ball, operating roller and synchronizing gear sets) is able to output varying torque moment and speed.

Comparing with IAP hands, the EAP prosthetic hands are superior in compactness, dexterity, actuation manner and power. Tendon actuation is usually adopted in EAP hand since there is sufficient space in the palm allowing for more active DOFs and sensors. In addition, the actuation components outside the hands are not limited by space anymore, by which motors with greater power can be used. On the other side, considering the overall volume and weight, IAP prosthetic hands

Liu *et al. Robomech J* (2016) 3:4

Page 3 of 9

Table 1 Dexterous robotic hands (selected)

Name	Fingers	Degree of freedom	Actuation configuration	Transmission mechanism	Ref.
Okada hand	3	11	Extrinsic	Tendon + Pulley	[6]
High-speed hand	3	8	Intrinsic	Harmonic reducer	[7]
Pinching hand	5	18	Intrinsic	Gear + Pulley	[8]
Ultrasonic hand	5	20	Intrinsic	Ultrasonic motors + Elastic elements	[9]
DLR-I hand	4	12	Intrinsic	Tendon	[10]
DLR-II hand	4	13	Intrinsic	Belt + Linkage + Gear	[11]
Dexhand	4	12	Hybrid	Tendon	[12]
DLR HASy hand	5	19	Extrinsic	Tendon	[13]
UB-II hand	3	11	Extrinsic	Tendon	[14]
UB-III hand	5	16	Extrinsic	Tendon	[15]
DIST hand	4	16	Extrinsic	Tendon	[16]
ARTS hand	5	11	Hybrid	Tendon + Gear + Worm	[17]
iCub hand	5	9	Hybrid	Tendon	[18]
Shadow hand	5	24	Extrinsic	Tendon	[19]
Stanford/JPL	3	9	Extrinsic	Tendon	[20]
Utah/MIT hand	4	16	Extrinsic	Tendon	[21]
Robonaut hand	5	14	Extrinsic	Tendon	[22, 23]
Extrinsic hand	5	11	Extrinsic	Tendon	[24]
Intrinsic hand	5	15	Intrinsic	Belt + Ballscrew	[25]
Gifu II hand	5	16	Intrinsic	Linkage + Gear	[26]
Gifu III hand	5	16	Intrinsic	Linkage + Gear	[27]
NAIST hand	4	12	Intrinsic	Linkage + Gear	[28]
NAIST hand 2	5	16	Extrinsic	Tendon + Gear	[29]
TWENTY-ONE	4	13	Intrinsic	Linkage + Gear	[30]
KIST hand	4	9	Intrinsic	Spatial linkage	[31]
ZJUT hand	5	20	Extrinsic	Flexible pneumatic actuator	[32]
DLR/HIT I	4	13	Intrinsic	Linkage + Gear	–
DLR/HIT II	5	15	Intrinsic	Belt + Tendon	–

usually use small-power direct current (DC) motors and tend to adopt a pre-tightening-free mechanism in actuation. Besides, the number of the sensors and embedded chips (CPU, ROM, etc.) are largely restricted such that sufficient information about the manipulation cannot be instantly processed. This problem could be solved along with the development of advanced electronic/computer engineering. One big merit of the IAP prosthetic hands is their application flexibility for different amputation degree. The individual difference of patients requires less re-design or re-configuration procedures for IAP prosthetic hand. Thus, these hands are more likely to be standardized, commercialized and maintained.

DLR/HIT dexterous robotic hands

The HIT-I hand (Fig. 1a) is our first dexterous hand prototype developed under a collaborative effort between Harbin Institute of Technology (HIT) and German Aerospace Center (DLR) in 2001. The HIT-I hand adopts a modular design concept that all four fingers (little finger excluded) are driven by embedded motors with tendons, because of which the degree of system integration is greatly improved and the size of the hand is well controlled at that time. Position sensor and force/torque gauges are embedded thus that the hand can accomplish some multisensory hand operations. However, due to the quality of the tendons and digital level of that time, the hand only promises a comparably low compatibility and robustness.

Based on HIT-I hand, refinement work for improving the mechanic/electronic reliability and human-like appearance is proposed in the design of DLR/HIT Hand I (Fig. 1b) [50]. Each finger is modularized as three joints with three active DOFs, wherein the metacarpophalangeal (MCP) joint has two active DOFs and the proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints had one active DOF (coupled through a four-bar linkage). In the metacarpal joint (TM) of the thumb, an

Liu *et al. Robomech J* (2016) 3:4

Page 4 of 9

Table 2 Anthropomorphic prosthetic hands (selected)

Name	Year 20~	Fingers joints DOF	Force velocity	Motors and configuration	Transmission mechanism	Size weight	Ref.
Cyber hand	03	5/15/16	70N 45°/s	6/DC Extrinsic	Tendon	95 % 360 g	[38]
Manus hand	04	5/10/4	60N 90°/s	3/BLDC Intrinsic	Tendon	120 % 300 g	[39]
IOWA hand	04	5/15/5	–	5/DC Intrinsic	Tendon	100 % 90 g	[40]
Fluid hand	04	5/8/8	110N 57°/s	1 Gear pump Intrinsic	8/Fluid actuator	100 % 350 g	[41]
Tokyo hand	05	5/15/12	0.4 Nm 200°/s	7/SM Extrinsic	Tendon	– 584 g	[42]
UB III	05	5/15/16	70N 250°/s	16/DC Extrinsic	Tendon	120 % –	[15]
SMA hand	08	5/15/7	– 41°/s	7/SMA Extrinsic	Tendon	50 % 250 g	[43]
Dong-Eui hand	08	5/15/6	14N –	6/DC Intrinsic	Tendon	– 400 g	[44]
Vanderbilt hand	09	5/16/17	–	5/GA Extrinsic	Tendon	– 580 g	[45]
Intrinsic hand	09	5/15/19	4.7 Nm 360°/s	15/BLDC Intrinsic	Motor	–	[46]
xtrinsic hand	09	5/11/21	– 360°/s	1/Cobot Extrinsic	Tendon	–	[47]
EA hand	09	5/16/5	80N 225°/s	5/DC Extrinsic	Tendon	100 % 580 g	[48]

DC direct current motor; *BLDC* brushless DC motor; *SM* servo motor; *SMA* Shape memory alloy actuators; *GA* gas actuator

Fig. 1 DLR/HIT dexterous hand prototypes. **a** HIT-I **b** DLR/HIT I **c** SAH hand
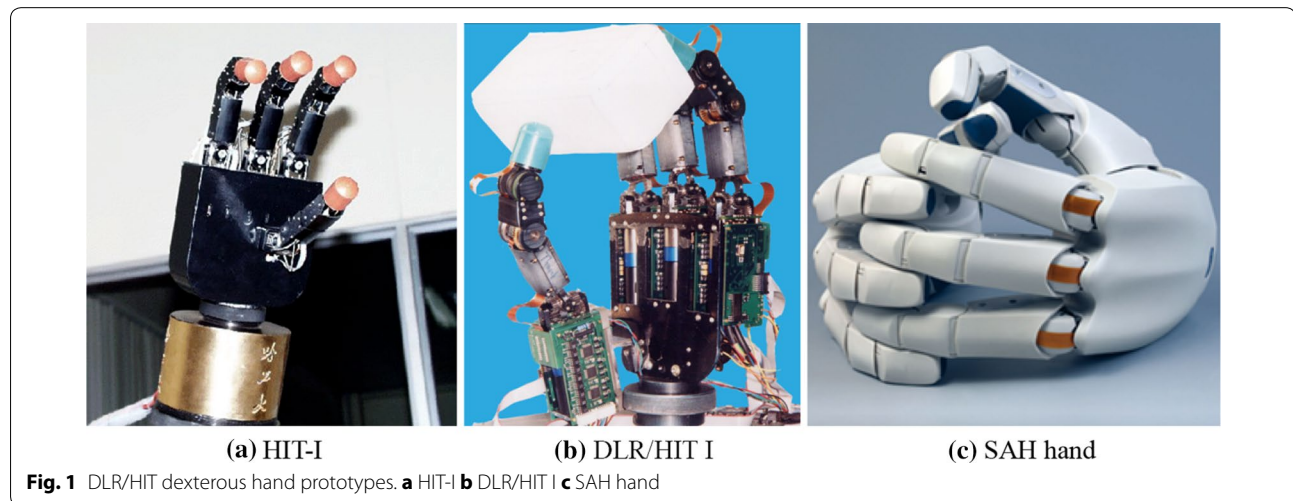
extra DOF is provided for realizing thumb opposition, thus that the relative position between thumb and four digits can be ensured in various grasping tasks. Gears, harmonic reducer, and linkages constitute to the hand's transmission system. The actuation and control system is totally embedded and digitalized as much as possible.

This design minimizes the hand's weight and reduces the number of tendons used for driving the joints. With collaboration of Schunk company, a commercialized version of the dexterous robot hand, SAH (Fig. 1c), is also available on the market and receives many success applications. The package design of the SAH largely improves its

Liu *et al. Robomech J* (2016) 3:4

Page 5 of 9

appearance and effectively protects the electronic system and cables within the hand.

In 2008, our newest generation DRH prototype, DLR/HIT Hand II [51], is presented with five identical fingers and a human-like curved palm, as Fig. 2 shows. To improve the hand's manipulation dexterity and operation intelligence, a total of 15 active DOFs and 140 sensors (position, force, temperature, and tactile) are integrated based on IAP. Each finger can be divided into two modulated units, 2-DOF basic joint unit and 1-DOF finger unit, within each the motors, reducers, sensors and electronic systems are totally built-in. By adopting micro brushless DC motors, timing belt, harmonic drive, and tendon coupling, the size and shape of DLR/HIT hand are significantly reduced (similar to an average mature hand). To further save space, sensors are tried to be integrated with the hand's mechanical structures, such as, the torque gauge is a transmission linkage in the basic joint, and the 3D tactile grid is an embedded layer on the finger pads. Attributed to its multimodal sensors, the DLR/HIT Hand II has a superior perception capability during various operation tasks.

Multi-fingered prosthetic hands

Since 2001, five prototypes of HIT-DLR anthropomorphic prosthetic hands (HITAPH) have been developed, as Table 3 shows. Designed based on DLR/HIT hand II, the HITAPH I–III has five fingers, and each is composed of three knuckles (2 knuckles in the thumb of HITAPH I and II). The HITAPH I–III are actuated by three DC motors, which are installed at the TM joint of the thumb, MCP joint of the index finger, and MCP joint of the middle finger, respectively. The middle finger, ring finger and little finger are co-actuated through torsional springs and linkages. Taking advantaging of the underactuation principal [52, 53], the inter-finger actuation of the hand is realized through elastic components, which provides the hands with an adaptive grasp to various objects. Among them, the HITAPH III [also called anthropomorphic robot (AR) hand III] [54] makes an improvement on its human-like appearance and grasp power.

Fig. 2 DLR/HIT Hand II

To further improve the hand's dexterity, the HITAPH IV [5] is developed with five active DOFs (that is, all five fingers are individually actuated). Attributed to advanced actuation techniques, the volume of the IAP hand is only 85 % of that of HITAPH III. The total hand weight is about 450 g. The output force at the fingertip can reach up to 10N. Curved palm and scattered finger configuration endow the hand with more anthropomorphic characters in appearance and grasping. Reducing the number of the non-standardized mechanical and electronic elements is one critical request in the design of HITAPH IV, aiming to improve the hand's interchangeability and maintainability. Meanwhile, the packaging design of the hand is also considered in the design, in connection with its actuation capacity, thermal and life design.

To further improve the thumb finger's mobility, an additional DOF is provided at the TM joint for realizing opposition. Attributed to this extra DOF, the thumb can reach to each fingertip of the other four fingers. Another big revision is the reduced number of knuckles, (two, instead of three in HITAPH IV [55]), for briefing the mechanical structure while keeping the hand's functionality and reliability. A total of six DC motors are embedded, while the actuation force at the fingertip can reach up to 12N. The worm gear, instead of bevel gears, is adopted in the MCP joints, while tendon coupling mechanism is maintained in the DIP joints. With addition to the position and force sensors, a 3-D tactile sensor [56] is designed that can measure one perpendicular force and two tangential forces applied on the fingertips. The number of the parts of the HITAPH IV is largely reduced compared with former prototypes, making it very promising in commercialization.

Challenges and future work

There are mainly two trends for developing DRHs, one is anthropomorphism-oriented and the other is task-oriented. For the first one, the robot hands are devised with much more human-like properties, as in its kinematics (hand structure, DOFs, grasping functionality, etc.), dynamics (stiffness, damping, friction, etc.), and perception capabilities (position sensors, force/torque sensors, tactile grid, slipping sensors, etc.). While for the task-oriented trend, the DRHs are designed according to some specialized tasks or environments, such as the Robonaut 2 hand and Dexhand, both for extravehicular activities on the ISS. Generally speaking, the word "anthropomorphism" is a very complicated concept including numerous influential factors that lacking anyone of them may lead to an underperformance design. Under current conditions, how to make a compromise between the hand's appearance and functionality, or how to establish a proper performance index [57] to compare design and

Liu *et al. Robomech J* (2016) 3:4

Page 6 of 9

Table 3 Specifications of the HIT-DLR anthropomorphic prosthetic hands

Picture	Name	Year	Fingers/ joints/ motors	actuation- transmission	Sensors	mass size	Force velocity
	HITAPH I	2003	5/14/3	Underactuated linkage + Belt 1-1-2	Position, torque	500 g 130 %	10N –
	HITAPH II	2005	5/14/3	Underactuated linkage + Belt 1-1-3	Position, torque	500 g 110 %	10N –
	HITAPH III	2007	5/15/3	Underactuated linkage 1-1-3	Position, torque	500 g 120 %	10N 72°/s
	HITAPH hand IV	2009	5/15/5	Coupling linkage 1-1-1-1-1	Position, torque	450 g 85 %	10N 89°/s
	HITAPH hand IV	2013	5/11/6	Tendon + Worm 2-1-1-1-1	Position, torque, 3D-tactile	475 g 80 %	12N 45°/s

thus make a suitable choice among alternatives, is still an urgent work in the robot hand research.

Attributed to its thumb's dexterity, the human hand can achieve so many versatile grasps and delicate operations. Decoding the thumb's movement in respect of DOF configuration is a big challenge in robotics research. We devote to analysis the thumb's movement based on human hand anatomy and biomechanics theory, and then to give a set of appropriate DOF configurations (TM-MCP-DIP, 2-1-1, 2-2-1 [58], 3-1-1 [59]) that can be used in DRHs for achieving a variety of dexterous operations. From the point of directional dexterity, we attempt to analyze these configurations on specific manipulation tasks, which can further facilitate our selection according to different application scenarios. How to arrange the thumb on the hand is another challenge. For achieving versatile and effective grasp patterns, an efficient method needs to be proposed for appropriately positioning the thumb on the palm.

The dexterous manipulations requested by the DRHs are not only promised by its anthropomorphic shape and motion, but also its high-speed processing system (sensor measurement, data analysis, kinematic calculation, etc.) and real-time control algorithms (task interpretation, motion planning, sensory feedback, etc.). Because of massive data calculation and interchange, selection of an appropriate control structure and platform, highly-integrated hardware and software hierarchy and suitable communication protocol are critical for DRH realizing a real-time manipulation. Currently, based on EtherCAT, a real-time control design and validation platform [60] has been developed, on which a large variety of algorithms,

Liu *et al. Robomech J* (2016) 3:4

Page 7 of 9

such as the impedance control strategy with coordinated multi-finger manipulation and optimized grasping forces [61], can be been verified.

For achieving delicate manipulations, the DRHs need to know necessary information about its outer environment (obstacles) and the object (stiffness, size, shape, and weight) to operate. The information is generally provides by our proprioception experiences (body schema) sensed by our central neural system through a long-term, multi-sensory stimulation (visual, tactile, force, tension, etc.). The tactile sensor [62] has been now widely integrated into the fingertip to acquire such information as the contact status, position, and some other physical properties (stiffness, texture, etc.) about the object. Even a primary haptic sense (object shape and category) can be reconstructed by using the tactile sensor and position sensors integrated on the robot hand. However, how to effectively fuse these information into the control scheme, thus to improve the hand's operation compliance, precision and intelligence, is still an open question [63].

The main task of a prosthetic hand is to to help physically disabled people restore hand functions in living environment (ADLs). General APHs should have three main features, as human-like appearance (size, weight, textures, compliance, etc.), mobility, and perception. Besides, state-of-the-art APHs request even more dexterous operations, given very limited choice on the actuation styles and DOF configurations. How to realize a large portion of human hand functions in very low actuation cost is very ambitious in APH research. Besides, high-precision position control (such as, to nip a needle) and accurate force control (such as, to grasp a fragile cup) are both frequently required in the daily use of APHs. How to devise a smart control strategy properly working on different conditions is another question. For controlling the prosthetic hands, the surface myoelectric signals (sEMG) collected from the residual neuromuscular system (stump) are widely accepted. Traditional mode-switching methods established on EMG amplitude only give very limited functions, discrete robot-like finger movements, and unintuitive control feelings. By introducing the pattern recognition method [64], a large progress has been made; however, there is still a big gap between the research and its real application [65, 66]. Intrinsic timing-varying characters of the EMG signals, environmental change (electromechanical status, temperature, moisture, sweating, etc.) of the bio-machine interface, and confounding factors (body postures, contraction strength variations, involuntary EMG activations) largely affect the long-term usage of clinical APHs. In this case, the control of APHs should consider other alternative peripheral nervous signals, such as ultrasonic signal [67], mechanomyography [68], near-infrared spectroscopy [69] and electrocorticography

[70], to be used in the control channel, and multi-sensory means [71], such as vision [72, 73] and tactile sense [74, 75], to be used in the feedback channel. With the big progress of the worldwide scientific research on artificial cognition and brain-computer interface, a fully-embodied hand avatar controlled by our brain with utmost ease will come soon.

Conclusions

This study focuses on the introduction of the development route of intrinsic actuation dexterous hands and prosthetic hands, giving a brief overview on the current artificial dexterous hands and prosthetic hands. With the progressing of science and technology, robotic hands are gradually approximating to human hands in dexterity and perception, based on which they can finish various complicated operations in the manufacturing process, activities of daily life, and exploration of unknown environment.

Authors' information
Liu H received the B.S. and the Ph.D. degrees from the Harbin Institute of Technology (HIT), Harbin, China, in 1986 and 1993, respectively. In 1991, he joined the German Aerospace Center (DLR) as joint Ph.D. candidate and worked on three finger robot hand. Since 1993, he has worked as a Key Researcher on the DLR four-finger Hand and the HIT/DLR five-finger Hand. In 1999, he received the Chang Jiang Scholars Program and received the Professorship of the HIT. Currently he is the head of School of Mechatronic Engineering, HIT and the director of the State Key Lab of Robotics and Systems. His research interests include space robotics, dexterous robot hands, and prosthetic hand systems.Yang DP received the B.S. degree in mechanic engineering from the Harbin Institute of Technology, in 2004, and the M.S. and Ph.D. degrees in mechatronic engineering from the Harbin Institute of Technology (HIT), in 2006 and 2011, respectively. Since 2011, he has been with the State Key Laboratory of Robotics and System, HIT, where he holds the position of an associated professor. His research interests include dexterous robotic/prosthetic hand systems, biomedical signal processing and control, human–machine interaction, and machine learning techniques in robotics.Fan SW received his B.S., M.S. and Ph.D. degrees in mechatronics engineering from Harbin Institute of Technology, Harbin, China, in 2001, 2005, and 2010, respectively. Since 2005, he has been with the State Key Laboratory of Robotics and System, Harbin Institute of Technology, where he currently holds the position of an associate researcher. His current research interests include anthropomorphic robot dexterous hand, prosthetics hand, tactile sensor, and grasping.Cai HG received the B.S. degree in mechanic engineering from the Harbin Institute of Technology, in 1958. Since 1985, he has been a professor at the School of Mechatronic Engineering, Harbin Institute of Technology. Since 1997, he has been an academician of the Chinese academy of engineering. Prof. Cai successfully developed China's first welding robots and spot welding robots, and solved critical problems in the robots' trajectory control accuracy and path predictive control. His current research interests include industrial robot, space robot and control algorithms.

Liu *et al. Robomech J* (2016) 3:4

Page 8 of 9

References
1. Pons JL, Ceres R, Pfeiffer F (1999) Multifingered dextrous robotics hand design and control: a review. Robotica 17(6):661–674
2. Bicchi A (2000) Hands for dexterous manipulation and robust grasping: a difficult road toward simplicity. IEEE Trans Robot Autom 16(6):652–662
3. Atkins DJ, Heard DC, Donovan WH (1996) Epidemiologic overview of individuals with upper-limb loss and their reported research priorities. J Prosthet Orthot 8(1):2–11
4. Peerdeman B, Boere D, Witteveen H, in't Veld RH, Hermens H, Stramigioli S, Rietman H, Veltink P, Misra S (2011) Myoelectric forearm prostheses: state of the art from a user-centered perspective. J Rehabil Res Dev 48(6):719–737
5. Liu H, Yang DP, Jiang L, Fan SW (2014) Development of a multi-DOF prosthetic hand with intrinsic actuation, intuitive control and sensory feedback. Ind Robot Int J 41(4):381–392
6. Okada T (1979) Object-handling system for manual industry. IEEE Trans Syst Man Cybern 9(2):79–89
7. Namiki A, Imai Y, Kaneko M, Ishikawa M (2004) Development of a high-speed Multifingered Hand System. In: Proceedings of the international conference on intelligent manipulation and grasping, Genova, pp 85–90
8. Hoshino K, Kawabuchi I (2005) Pinching with finger tips in humanoid robot hand. In: Proceedings, 12th international conference on Advanced robotics ICAR, IEEE, 2005, pp 705–712
9. Yamano I, Maeno T (2005) Five-fingered robot hand using ultrasonic motors and elastic elements. In: Proceedings of the 2005 IEEE international conference on robotics and automation ICRA, IEEE, pp 2673–2678
10. Hirzinger G, Fischer M, Brunner B, Koeppe R, Otter M, Grebenstein M, Schäfer I (1999) Advances in robotics: the DLR experience. Int J Robot Res 18(11):1064–1087
11. Butterfaß J, Grebenstein M, Liu H, Hirzinger G (2001) DLR-Hand II: Next generation of a dextrous robot hand. In: Proceedings 2001 IEEE international conference on robotics and automation ICRA. IEEE, pp 109–114
12. Chalon M, Wedler A, Baumann A, Bertleff W, Beyer A, Butterfaß J, Grebenstein M, Gruber R, Hacker F, Kraemer E Dexhand (2011) A Space qualified multi-fingered robotic hand. In: IEEE international conference on robotics and automation ICRA, IEEE, pp 2204–2210
13. Grebenstein M, Albu-Schäffer A, Bahls T, Chalon M, Eiberger O, Friedl W, Gruber R, Haddadin S, Hagn U, Haslinger R The DLR hand arm system (2011) In: IEEE international conference on robotics and automation ICRA, IEEE, pp 3175–3182
14. Melchiorri C, Vassura G (1994) Implementation of whole-hand manipulation capability in the UB hand system design. Adv Robot 9(5):547–560
15. Lotti F, Tiezzi P, Vassura G, Biagiotti L, Palli G, Melchiorri C (2005) Development of UB hand 3: early results. In: Proceedings of the 2005 IEEE international conference on robotics and automation ICRA, IEEE, pp 4488–4493
16. Caffaz A, Cannata G (1998) The design and development of the DIST-Hand dextrous gripper. In: Proceedings. 1998 IEEE international conference on robotics and automation, IEEE, 1998, pp 2075–2080
17. Controzzi M, Cipriani C, Jehenne B, Donati M, Carrozza MC (2010) Bio-inspired mechanical design of a tendon-driven dexterous prosthetic hand. In:2010 annual international conference of the IEEE on engineering in medicine and biology society (EMBC), IEEE, pp 499–502
18. Schmitz A, Pattacini U, Nori F, Natale L, Metta G, Sandini G (2010) Design, realization and sensorization of the dexterous iCub hand. In: 2010 10th IEEE-RAS international conference on humanoid robots (humanoids), IEEE, pp 186–191
19. Shadow Dexterous Hand™—Now available for purchase! http://www.shadowrobot.com/products/dexterous-hand/ Accessed 01.08.2016
20. Mason MT, Salisbury JK Jr (1985) Robot hands and the mechanics of manipulation. The MIT Press, Cambridge, pp 3–93
21. Jacobsen SC, Wood JE, Knutti D, Biggers KB (1984) The UTAH/MIT dextrous hand: work in progress. Int J Robot Res 3(4):21–50
22. Lovchik C, Diftler MA (1999) The robonaut hand: A dexterous robot hand for space. In: Proceedings. 1999 IEEE international conference on robotics and automation, IEEE, pp 907–912
23. Bridgwater LB, Ihrke C, Diftler MA, Abdallah ME, Radford NA, Rogers J, Yayathi S, Askew RS, Linn DM (2012) The robonaut 2 hand-designed to do work with tools. In: 2012 IEEE international conference on robotics and automation (ICRA), IEEE, pp 3425–3430
24. Mitchell M, Weir RF (2008) Development of a clinically viable multifunctional hand prosthesis. Proceedings of the 2008 myoelectric controls/powered prosthetics symposium, Fredericton. IEEE, New Brunswick, pp 45–49
25. Weir R, Mitchell M, Clark S, Puchhammer G, Haslinger M, Grausenburger R, Kumar N, Hofbauer R, Kushnigg P, Cornelius V (2008) The intrinsic hand–a 22 degree-of-freedom artificial hand-wrist replacement. Proceedings of myoelectric controls powered prosthetics symposium, IEEE, New Brunswick, 233–237
26. Kawasaki H, Komatsu T, Uchiyama K (2002) Dexterous anthropomorphic robot hand with distributed tactile sensor: gifu hand II. IEEE/AMSE Trans Mechatron 7(3):296–303
27. Mouri T, Kawasaki H, Yoshikawa K, Takai J, Ito S (2002) Anthropomorphic robot hand: Gifu hand III. Proceedings of the 2002 IEEE international conference on autonomic and autonomous systems, Jeonbuk. Korea, IEEE, pp 1288–1293
28. Ueda J, Kondo M, Ogasawara T (2010) The multifingered NAIST hand system for robot in-hand manipulation. Mech Mach Theory 45(2):224–238
29. Kurita Y, Ono Y, Ikeda A, Ogasawara T (2011) Human-sized anthropomorphic robot hand with detachable mechanism at the wrist. Mech Mach Theory 46(1):53–66
30. Iwata H, Sugano S (2009) Design of anthropomorphic dexterous hand with passive joints and sensitive soft skins. In: SII 2009. IEEE/SICE International Symposium on System Integration, IEEE, pp 129–134
31. Kim E-H, Lee S-W, Lee Y-K (2011) A dexterous robot hand with a biomimetic mechanism. Int J Precis Eng Manufactur 12(2):227–235
32. Wang ZH, Zhang LB, Gzj Bao, Qian SM, Yang QH (2011) Design and control of integrated pneumatic dexterous robot finger. J Central South Univ Technol 18:1105–1114
33. Schäffer A, Eiberger O, Grebenstein M, Haddadin S, Ott C, Wimböck T, Wolf S, Hirzinger G (2008) Soft robotics, from torque feedback-controlled lightweight robots to intrinsically compliant systems. IEEE Robot Autom Mag 15(3):20–30
34. Kyberd PJ, Chappell PH (1994) The southampton hand: an intelligent myoelectric prosthesis. J Rehabil Res Dev 31(4):326–334
35. Kyberd PJ, Evans MJ, Winkel S (1998) An intelligent anthropomorphic hand with automatic grasp. Robotica 16:531–536
36. Dashy R, Yen C, Leblanc M (1998) The design and development of a gloveless endoskeleton prosthetic hand. J Rehabil Res Dev 35(4):388–395
37. Huang HP, Chen CY (1999) Development of a myoelectric discrimination system for a multi-degree prosthetic hand. Proceedings of the 1999 IEEE international conference on robotics and automation, detroit. Michigan, IEEE, pp 2392–2397
38. Carrozza MC, Cappiello G, Micera S, Edin BB, Beccai L, Cipriani C (2006) Design of a cybernetic hand for perception and action. Biol Cybern 95:629–644
39. Pons JL, Rocon E, Ceres R (2004) The MANUS-HAND dextrous robotics upper limb prosthesis: mechanical and manipulation aspects. Autonomous Robots 16:143–163
40. Yang J, Pitarch EP, Abdel-Malek K, Patrick A, Lindkvist L (2004) A multifingered hand prosthesis. Mech Mach Theory 39(6):555–581
41. Kargov A, Werner T, Pylatiuk C, Schulz S (2008) Development of a miniaturised hydraulic actuation system for artificial hands. Sens Actuators, A 141(2):548–557
42. Arieta AH, Katoh R, Yokoi H, Wenwei Y (2006) Development of a multi-DOF electromyography prosthetic system using the adaptive joint mechanism. Appl Bion Biomech 3(2):101–111
43. Andrianesis K, Tzes A (2008) Design of an anthropomorphic prosthetic hand driven by shape memory alloy actuators. In: Proceedings of the 2nd Biennial IEEE/RAS-EMBS international conference on biomedical robotics and biomechatronics, biorob, pp 517–522
44. Jung SY, Moon I (2008) Grip force modeling of a tendon-driven prosthetic hand. In: 2008 international conference on control, automation and systems, ICCAS, Seoul, pp 2006–2009

Liu *et al. Robomech J* (2016) 3:4

Page 9 of 9

45. Fite KB, Withrow TJ, Shen X, Wait KW, Mitchell JE, Goldfarb M (2008) A gas-actuated anthropomorphic prosthesis for transhumeral amputees. IEEE Trans Rob 24(1):159–169

46. Weir R, Mitchell M, Clark S, Puchhammer G, Haslinger M, Grausenburger R, Kumar N, Hofbauer R, Kushnigg P, Cornelius V (2008) The intrinsic hand–a 22 degree-of-freedom artificial hand-wrist replacement. In: Proceedings of myoelectric controls/powered prosthetics symposium, New Brunswick, pp 233–237

47. Mitchell M, Weir R F (2008) Development of a clinically viable multifunctional hand prosthesis. In Proceedings of the 2008 myoelectric controls powered prosthetics symposium Fredericton, IEEE, New Brunswick, p 45–49

48. Dalley SA, Wiste TE, Withrow TJ, Goldfarb M (2009) Design of a multi-functional anthropomorphic prosthetic hand with extrinsic actuation. Mechatron, IEEE/ASME Trans 14(6):699–706

49. Kinea Design LLC. (2011). http://www.kineadesign.com. Accessed 08 Apr 2011

50. Liu H, Meusel P, Hirzinger G, Jin M, Liu Y, Xie Z (2008) The modular multi-sensory DLR-HIT-Hand: hardware and software architecture. IEEE/ASME Trans Mechatron 13(4):461–469

51. Liu H, Wu K, Meusel P, Seitz N, Hirzinger G, Jin M, Liu Y, Fan S, Lan T, Chen Z (2008) Multisensory five-finger dexterous hand: The DLR/HIT Hand II. In: IEEE/RSJ international conference on intelligent robots and systems IROS, IEEE, pp 3692–3697

52. Dechev N, Cleghorn W, Naumann S (2001) Multiple finger, passive adaptive grasp prosthetic hand. Mech Mach Theory 36(10):1157–1173

53. Laliberté T, Birglen L, Gosselin C (2002) Underactuation in robotic grasping hands. Machine Intell Robot Control 4(3):1–11

54. Yang D, Zhao J-d Gu, Y-k Wang X-q, Li N, Liu H, Jiang L, Huang H, D-w Zhao (2009) An anthropomorphic robot hand developed based on underactuated mechanism and controlled by emg signals. J Bionic Eng 6(3):255–263

55. Jiang L, Zeng B, Fan S, Sun K, Zhang T, Liu H A (2014) modular multisensory prosthetic hand. In: 2014 IEEE international conference on information and automation (ICIA), IEEE, pp 648–653

56. Zhang T, Liu H, Jiang L, Fan S, Yang J (2013) Development of a flexible 3-d tactile sensor system for anthropomorphic artificial hand. IEEE Sens J 2:510–518

57. Hioki M, Ebisawa S, Sakaeda H, Mouri T, Nakagawa S, Uchida Y, Kawasaki H (2011) Design and control of electromyogram prosthetic hand with high grasping force. In: 2011 IEEE international conference on robotics and biomimetics (ROBIO), IEEE, pp 1128–1133

58. Santos VJ, Valero-Cuevas FJ (2006) Reported anatomical variability naturally leads to multimodal distributions of Denavit-Hartenberg parameters for the human thumb. Biomed Eng, IEEE Trans 53(2):155–163

59. Rezzoug N, Gorce P (2008) Prediction of fingers posture using artificial neural networks. J Biomech 41(12):2743–2749

60. Hou M, Jiang L, Jin M, Liu H, Chen Z (2014) Analysis of the multi-finger dynamics for robot hand system based on EtherCAT. In: 2014 10th international conference on natural computation (ICNC), IEEE, pp 1061–1065

61. Hou M, Jiang L, Jin M, Liu H, Chen Z (2014) Strategies to optimize fingertip force for impedance control of robot hand based on EtherCAT.

In: Proceedings of the 2014 Asia-Pacific conference on computer science and applications (CSAC 2014) computer science and applications, CRC Press, Shanghai, p 245

62. Antfolk C, Balkenius C, Rosen B, Lundborg G, Sebelius F (2010) SmartHand tactile display: a new concept for providing sensory feedback in hand prostheses. Scand J Plast Reconstr Surg Hand Surg 44(1):50–53

63. Raspopovic S, Capogrosso M, Petrini FM, Bonizzato M, Rigosa J, Di Pino G, Carpaneto J, Controzzi M, Boretius T, Fernandez E (2014) Restoring natural sensory feedback in real-time bidirectional hand prostheses. Sci transl med 6(222):222ra219

64. Fang Y, Hettiarachchi N, Zhou D, Liu H (2015) Multi-modal sensing techniques for interfacing hand prostheses: a review. Sensors J IEEE 15(11):6065–6076

65. Castellini C, Artemiadis P, Wininger M, Ajoudani A, Alimusaj M, Bicchi A, Caputo B, Craelius W, Dosen S, Englehart K, Farina D, Gijsberts A, Godfrey SB, Hargrove L, Ison M, Kuiken T, Markovic M, Pilarski P, Rupp R, Scheme E (2014) Proceedings of the first workshop on peripheral machine interfaces: going beyond traditional surface electromyography. Front Neurorobotics 8 22:21. doi:10.3389/fnbot.2014.00022

66. Ning J, Dosen S, Muller KR, Farina D (2012) Myoelectric control of artificial limbs: is there a need to change focus? IEEE Signal Process Mag 29(5):148–152

67. Ravindra V, Castellini C (2014) A comparative analysis of three non-invasive human-machine interfaces for the disabled. Front neurorobotics 8:24. doi:10.3389/fnbot.2014.00024

68. Chen X, Zheng YP, Guo JY, Shi J (2010) Sonomyography (SMG) control for powered prosthetic hand: a study with normal subjects. Ultrasound Med Biol 36(7):1076–1088

69. Siesler HW, Ozaki Y, Kawata S, Heise HM (2008) Near-infrared spectroscopy: principles, instruments, applications. Wiley, New York

70. Fifer MS, Acharya S, Benz HL, Mollazadeh M, Crone NE, Thakor NV (2012) Towards electrocorticographic control of a dexterous upper limb prosthesis. IEEE PULSE 3(1):38–42

71. McMullen DP, Hotson G, Katyal KD, Wester BA, Fifer MS, McGee TG, Harris A, Johannes MS, Vogelstein RJ, Ravitz AD, Anderson WS, Thakor NV, Crone NE (2014) Demonstration of a semi-autonomous hybrid brain-machine interface using human intracranial eeg, eye tracking, and computer vision to control a robotic upper limb prosthetic. Neural Syst Rehabil Eng, IEEE Trans 22(4):784–796. doi:10.1109/TNSRE.2013.2294685

72. Markovic M, Dosen S, Cipriani C, Popovic D, Farina D (2014) Stereovision and augmented reality for closed-loop control of grasping in hand prostheses. J Neural Eng 11(4):046001

73. Markovic M, Dosen S, Popovic D, Graimann B, Farina D (2015) Sensor fusion and computer vision for context-aware control of a multi degree-of-freedom prosthesis. J Neural Eng 12(6):066022

74. Riso RR (1999) Strategies for providing upper extremity amputees with tactile and hand position feedback–moving closer to the bionic arm. Technol Health Care 7(6):401–409

75. Kyberd PJ, Mustapha N, Carnegie F, Chappell PH (1993) A clinical experience with a hierarchically controlled myoelectric hand prosthesis with vibro-tactile feedback. Prosthet Orthot Int 17(1):56–64