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A MODULAR APPROACH FOR LIGHTWEIGHT HUMANOID HAND DESIGN USING HIGH TORQUE DENSITY ELECTRIC ACTUATORS

Haotian Cui
Department of Mechanical Engineering,
City College of New York
New York, NY, USA

Shuangyue Yu
Department of Mechanical Engineering,
City College of New York
New York, NY, USA

Xunge Yan
INNFOS(Beijing) Technology Co., Ltd.
Beijing, Beijing, China

Shuo-Hsiu Chang
Department of Physical Medicine and
Rehabilitation, University of Texas Health Science
Center at Houston (UTHealth),
Houston, Texas, USA

Gerard Francisco
Department of Physical Medicine
and Rehabilitation, University of
Texas Health Science Center at
Houston (UTHealth),
Houston, Texas, USA

Qiushi Fu
Depart of Mechanical and
Aerospace Engineering,
University of Central Florida,
Orlando, Florida, USA

Hao Su
Department of Mechanical
Engineering,
City College of New York
New York, NY, USA

BACKGROUND

The human hand has extraordinary dexterity with more than 20 degrees of freedom (DOF) actuated by lightweight and efficient biological actuators (i.e., muscles). The average weight of human hand is only 400g [1]. Over the last few decades, research and commercialization effort has been dedicated to the development of novel robotic hands for humanoid or prosthetic application towards dexterous and biomimetic design [2]. However, due to the limitations of existing electric motors in terms of torque density and energy efficiency, the design of humanoid hands has to compromise between dexterity and weight. For example, commercial prosthetic terminal devices i-Limb [3] and Bebionic [4] prioritize the lightweight need (450g) and use 5-DOF motors to under-actuated 11 joints, which is only able to realize a few basic grasp postures. On the other hand, some humanoid robot hand devices like DLR-HIT I & II hands [5] prioritize the dexterity need (15 DOF), but weigh more than four times than their biological counterpart (2200g and 1500g, respectively).

The contribution of this work is the development of a custom high-torque density electric actuator and its application

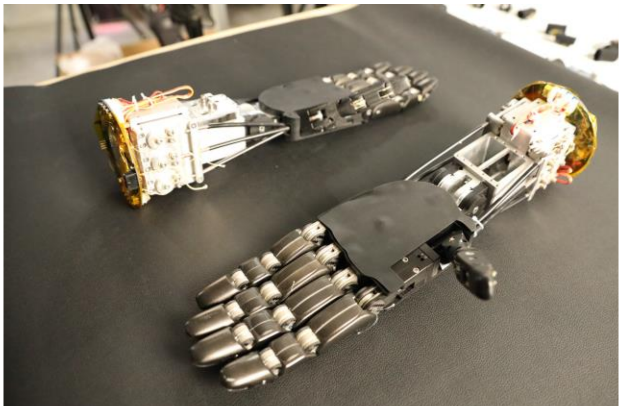


Fig 1. The lightweight and energy-efficient humanoid hand have 9 actuated DOF. All 9 actuators are embedded inside the wrist module and provide under-actuation for 14 joints. The dimension and weight of the hand are similar to a male adult hand.

for the modular design approach of a lightweight humanoid hand, as shown in Fig. 1. The proposed electric actuators are developed with new motor topology and permanent magnetic materials; thus, our innovation is in the motor level instead of

Haotian Cui was with the INNFOS(Beijing) Technology Co., Ltd.

modification of existing motors. Our motor design is fundamentally different with actuators like series electric actuators (SEA) that typically use commercially available motors (e.g. Maxon Motor, Switzerland) with external springs as a compliant mechanism. In comparison with conventional motors, this novel actuator provides higher torque density, thus it effectively improves the grasping force while reducing the overall weight.

METHODS

As shown in Fig. 2, the humanoid hand has 9 actuated DOFs to control 14 joints. Specifically, the thumb consists of a 2-DOF controlled carpometacarpal joint, and 1-DOF controlled metacarpophalangeal (MCP) and interphalangeal joints. The index finger consists of 2-DOF, one can control MCP joint abduction-adduction movement and another for MCP, proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints flexion-extension movement. The other three fingers all have 1-DOF controlled MCP, PIP, and DIP. The wrist join has 1-DOF for the flexion-extension movement control.

The weight and dimension of the humanoid hand are anatomically similar to adult human hands. Its weight is about 750g and consists of the hand subsystem (palm and five fingers, about 300g) and the wrist subsystem (about 450g). The dimension of hand module is 215mm (length) × 130mm (width) × 20mm (thickness). The wrist module is kinematically similar to a circular truncated cone with 80mm distal diameter, 100mm proximal diameter, and 150mm in length.

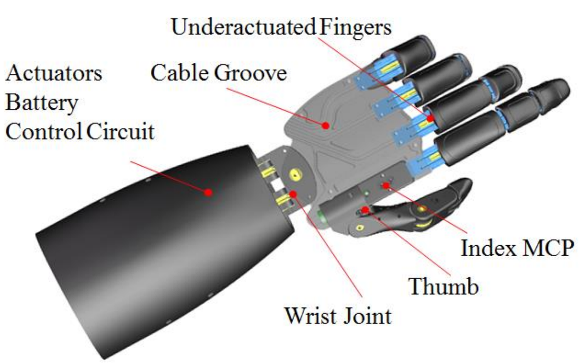
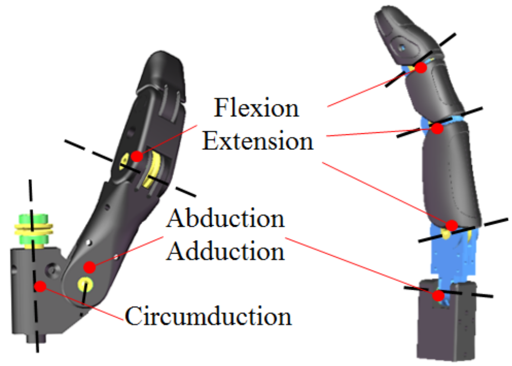


Fig 2. The wrist module has 9 electric actuators, 12 V battery and control circuit. One actuator controls the wrist joint and the remaining 8 actuators are cable-driven (along with the groove) to control individual finger joint.

The human thumb and index fingers are very dexterous and play a key role in the manipulation tasks. Thus, the thumb joint has 3 DOF to coordinately control the thumb mechanism, and provide opposition, abduction-adduction, and flexion-extension movement. The index finger has 2 DOF to control the abduction-adduction and flexion-extension movement, as shown in Fig. 3.



(a) Thumb finger module (b) Index finger module

Fig 3. Design of Thumb and Index finger module. Thumb finger module has three DOF and Index finger module has two DOF.

In order to minimize mass and footprint of the hand, actuators and battery are placed inside the wrist module. The cable-driven design transmits motion between actuators and each joint of the hand. The flexion/extension movement of each finger's MCP, DIP and PIP joints are under-actuated by the single cable-actuated actuator, which can linear-control every joint's flexion-extension movement in the same torque. The cable is made by Teflon material and tied on each joint to overcome the cable elasticity, which will help to enhance control accuracy and reduce hysteresis.

As shown in Fig. 4, a modular design has been developed for other four fingers' flexion-extension joint movement. Four pieces of finger skeleton are made by carbon fiber bracket and magnesium alloy supporting parts, and connect one by one through MCP, PIP and DIP joint. The finger skeleton and cable are covered by a 3D-printed shell. Between the shell and finger skeleton, custom-made silica gel filler is not only used to fix the cable but also works as a buffer to defend external shocks and enhance contact area, which will help the hand get a better behavior when grasp items. Besides, a crown block system with two group of cable - likes the structure which is wildly used in the curtain - is designed in each flexion-extension joint to guarantee both flexion/extension can be same controlled.

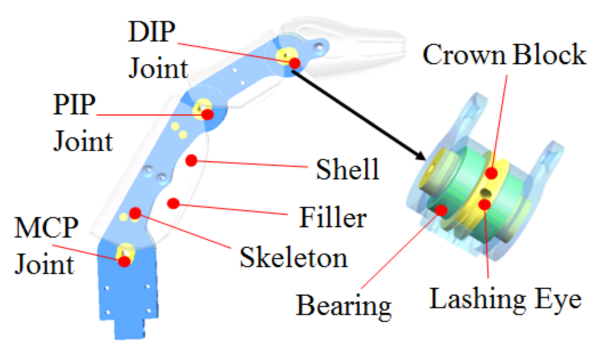


Fig 4. The modular design of non-thumb finger joints. Each modular finger consists of four pieces of the metal skeleton and three joints, which is covered by silica gel filler and 3D-printed shell. Each flexion-extension joint mainly consists of two miniature bearings for symmetry placement and a custom-designed bearing with lashing eye. Two cables

are placed along both sides of the bearing and knotted in the lashing eye.

In the current version of this hand, the off-the-shelf electric actuators (K-power Servo, China) have relatively low torque mass density (28g, 4.5kg/cm, 7.4v) and slow response speed (0.2sec/60°). To further reduce the weight of the humanoid hand, the high torque density electric actuators have been developed and are being incorporated in the new hand design, as shown in Fig. 5.

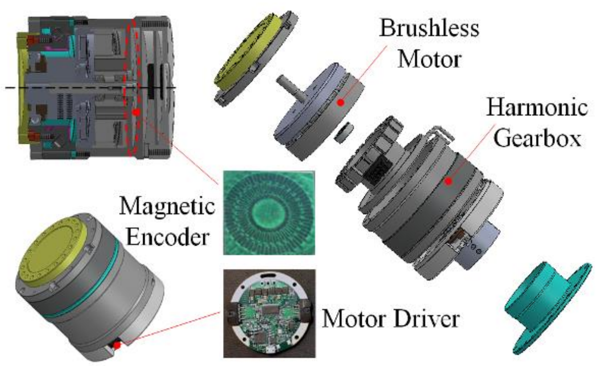


Fig 5. Custom designed high torque density electric actuator. It is composed of a outer-rotor brushless motor, a harmonic drive, a magnetic absolute position encoder and a driver electronics.

RESULTS

Table 1 shows the performance comparison between our model (MSC-70-H50) and HEBI-Robotics (X8-9, Biorobotics Lab, Carnegie Mellon University), which have nearly same weight. As can be seen, the designed actuation system has good performance in power density, output torque, respond speed, control accuracy, and even efficiency.

Table 1. Our design compared with HEBI

Property	Our motor	HEBI Robotics
Model	MSC-70-H50	X8-9
Mass (g)	450	480
Size (mm)	ϕ70 × 74 (L)	110 (L) × 73(W) × 45 (H)
Power Density (W/kg)	222	52
Rated Torque (NM)	14	8
Peak Torque (NM)	45	20
Rated Speed (RPM)	120	30
Accuracy (arcmin)	1	15
Power Efficiency (%)	65	35

Fig. 6 shows the whole series size of our custom-designed electric motor, and the minimum diameter – just 10mm - is pretty smaller than a cent coin (19.1mm). In ideal conditions, the scale down electrics actuator for finger actuation will less than 25g and maximum output torque reach to 2Nm. It mainly includes a custom-made tiny outer-rotor brushless motor which has 0.616mNm maximum output torque and a three-stage planetary reducer which ratio is about to 325:1.

Fig 6. The size range of our custom-designed electric actuators are from 10mm to 100mm and have different output torque.

Table 2 shows that under the same design condition (the 9 DOF cable-drive humanoid hand, 20% transmission loss), the main difference between using former actuation and the scale downed actuators. As can be seen in Table 2, although using the designed electrics actuator will just limit contribute to reducing the weight of the system (about 37g - 5% reduction), the humanoid hand will have 5 times higher finger grasp force than currently-used actuators.

Table 2. Performance comparisons before and after the actuator replacement

Property	Currently Used Actuator	Custom-made Actuator
Unit Weight (g)	28	25
Number of Actuators	9	9
Totally Weight (g)	252	225
Output Torque (Nm)	0.45	2
Transmission loss (%)	20	20
Finger Grasp Torque (Nm)	0.36	1.6

The experiment shows the grasping posture with a variety of objects. We simply control the actuation to the target angles and let the electric motor continuous output torque. As shown in Fig. 7, the humanoid hand can grasp different objects with a variety of grasp postures from Cutkosky grasp taxonomy [6]. The anthropomorphic design of the hand enables natural and stable grasps with the large contact area.

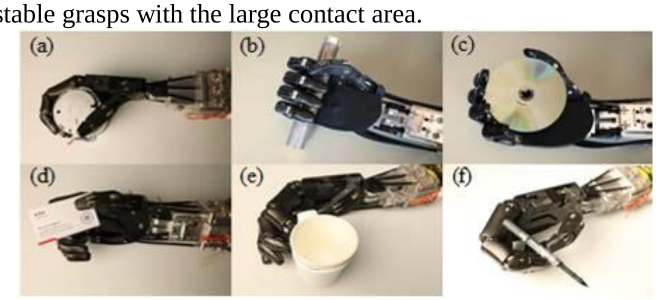


Fig 7. Example grasping postures with various objects: (a) spherical power grasp, (b) cylinder power grasp, (c) five-finger precision grasp, (d) (e) two-finger precision grasp, (f) three-finger precision grasp.

INTERPRETATION

This paper proposed the design of a lightweight humanoid hand and described the mechatronic components including a novel high torque density electric actuator. The hand subsystem has a modular finger design and uses single-DOF to under-actuated MCP, PIP and DIP joints' flexion-extension movements. Besides, a series of the electric motor has been designed with the main performance of high torque mass density, respond speed, control accuracy and efficiency. A scale down version will perfectly suit for being used as an actuator of finger joints for soft exoskeleton and prosthetics.

Our future goal is to leverage the actuator innovation and modular design approach to develop partial prosthetic fingers with tactile sensing: 1) use the cable-driven design for soft exoskeleton and prosthetics. The system will obtain desirable backdrivable capability and maintain human-robot interaction safe; 2) further reduce the overall mass of the hand by reducing the number of actuated DOFs with the concept of postural synergy [7], as well as 3) add tactile sensing components using fiber optic sensors. These would allow optimization for the trade-off between functionality and weight, leading to an ideal and practical design of humanoid and prosthetic hands.

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