Open-Source, Affordable, Modular, Light-Weight, Underactuated Robot Hands

Agisilaos G. Zisimatos, Minas V. Liarokapis, Christoforos I. Mavrogiannis and Kostas J. Kyriakopoulos

Abstract— **In this paper we present a series of design directions for the development of affordable, modular, light-weight, intrinsically-compliant, underactuated robot hands, that can be easily reproduced using off-the-shelf materials. The proposed robot hands, efficiently grasp a series of everyday life objects and are considered to be general purpose, as they can be used for various applications. The efficiency of the proposed robot hands has been experimentally validated through a series of experimental paradigms, involving: grasping of multiple everyday life objects with different geometries, myoelectric (EMG) control of the robot hands in grasping tasks, preliminary results on a grasping capable quadrotor and autonomous grasp planning under object position and shape uncertainties.**

Index Terms: **Underactuated Robot Hands, Open Source Design, Affordable Robots.**

I. Introduction

The problem of grasping has been one of the greatest topics of robotics research, during the last fifty years, as roboticists were always intrigued to understand and be inspired by nature's most versatile and dexterous end-effector, the human hand. The first robot hands, were actually simple robot grippers, with a limited number of Degrees of Freedom (DoFs), which were capable of grasping a limited set of objects with simple geometry, located in a-priori known static environments. Nowadays grippers are still the most common alternative for robotic grasping, both in industry and research [1], [2], due to their low-complexity and relatively low cost. But the state-of-the-art of robot hands follows the road to increased performance and humanlikeness [3], which leads also undoubtedly to increased complexity and of course increased cost. The issue of cost is definitely not negligible and nowadays robot hands cost thousands of USD, due to the materials used, the complex design and the sophisticated actuators and sensors. Are their grasping capabilities analogous to their price? Our subjective opinion is that the answer is no and that the problem of grasping can become remarkably complex or even remarkably simple, depending on the design choices. A nice collection of different robot hand designs was presented in [4].

Agisilaos G. Zisimatos, Minas V. Liarokapis and Kostas J. Kyriakopoulos are with the Control Systems Lab, School of Mechanical Engineering, National Technical University of Athens, 9 Heroon Polytechniou Str, Athens, 15780, Greece. Email: mliaro@mail.ntua.gr, el08087@mail.ntua.gr, kkyria@mail.ntua.gr

Christoforos I. Mavrogiannis is with the Sibley School of Mechanical & Aerospace Engineering, Cornell University, Ithaca, NY 14853, USA. Email: cm694@cornell.edu

This work has been partially supported by the European Commission with the Integrated Project no. 248587, THE Hand Embodied, within the FP7-ICT-2009-4-2-1 program Cognitive Systems and Robotics.

Over the last 10 years a series of studies have focused on low-cost robot hands based on elastomer materials or elastic hinges, that in some cases were also open-source [5], providing directions for the replication of the design. More specifically, in [6] authors presented the development of the humanoid robot hand UB (University of Bologna) Hand 3. This hand is based on an endoskeleton made of rigid links connected with elastic hinges, which is actuated by artificial tendons and the whole hand is covered by compliant pulps. In [7] the highly compliant RBO robot hand was proposed, which is based on a novel pneumatic actuator called PneuFlex. A new design approach for robot hands created using polymer-based shape deposition manufacturing, was first proposed in [8] by Dollar et al. and led eventually to the creation of the highly adaptive SDM hand [9]. The SDM hand is equipped with cable driven fingers, that have viscoelastic flexure joints, stiff links, soft fingerpads and a set of movable pulleys, as a differential mechanism. In [10] an underactuated robot hand with force and joint angle sensors, equipped with a novel movable block differential mechanism, was proposed. Recently, a dexterous gripper with active surfaces, the velvet fingers was proposed [11]. This latter hand, despite its underactuated design, is capable of performing manipulation tasks, using the active surfaces to apply tangential thrust to the contacted object. Another example of a recent underactuated, compliant robot hand, is the i-HY (iRobot-Harvard-Yale) hand [12], which was created for robust grasping, manipulation and in-hand manipulation of everyday life objects. i-HY hand has 5 actuators and fingers equipped with flexure joints and integrated tactile arrays. Finally, an example of a commercially available, compliant robot hand is the Meka H2 hand [13], which consists of 5 elastic actuators, driving 12 joints of four fingers made of urethane, in an underactuated design. It must be noted, that the aforementioned studies have made progress towards the goal of reducing the hand cost and weight. Thus the minimum cost is nowadays 400 USD and the minimum weight is 400 gr (0.88 lb), as reported in [5].

In this paper we propose a new design approach, for the creation of affordable (less than 100 USD), light-weight (less than 200 gr | 0.44 lb), intrinsically-compliant, underactuated robot hands, that can be easily reproduced with off-the-shelf materials. Extensive experimental paradigms are provided, for grasping of numerous everyday life objects, myoelectric (EMG) control of the robot hands, some preliminary results on a grasping capable quadrotor (using an aerial gripper) and autonomous grasp planning under object position and shape uncertainties, as part of a robot arm hand system.

The rest of the paper is organized as follows: Section II presents the open-source design, Section III presents extensive experimental paradigms and possible applications for the robot hands developed, while Section IV concludes the paper.

II. Open Source Design

A. Bioinspired Design of Robot Fingers

The low-cost design, for affordable, underactuated, compliant robot hands that we present in this study, is based on a simple but yet effective idea: to use agonist and antagonist forces to implement flexion and extension of robot fingers, following a bioinspired approach where steady elastomer materials implement the human extensor tendons counterpart, while cables driven through low-friction tubes implement the human flexor tendons analogous, as depicted in Fig. 1.

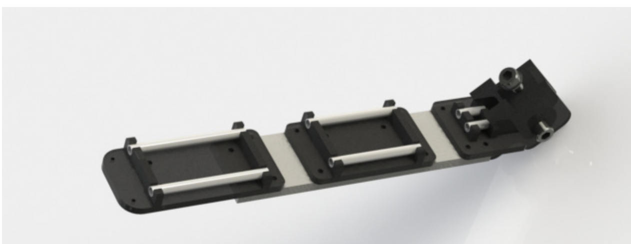

Fig. 1: The structure of one robot finger is presented. The elastomer materials appear at the lower part of the image (white sheets), while the low-friction tubes that are used for tendon routing, appear at the upper part of the image (white tubes) together with the rigid phalanges. The finger base is also depicted at the right part of the figure. For the assembly of the robot fingers we use fishing line and needles in order to stitch the silicone sheets onto the rigid links (the links have appropriate holes by design).

Recently we proposed a complete methodology based on computational geometry and set theory methods in order to quantify anthropomorphism of robot hands [14]. The idea was simple and clear, to compare robot hands with the most versatile and dexterous end-effector known, the human hand, in order to extract design specifications. Specifications according to which the object surrounding us have been crafted. But in order to extract those specifications, a new metric was necessary, a metric that would quantify the humanlikeness of robot hands in terms (at least) of kinematic similarity. This latter metric rates the kinematic similarity of any robot hand with the human hand and derives a score that ranges between 0 (non-humanlike) and 1 (human-identical). Although in this study we are not proposing anthropomorphic robot hands, we used this metric and the related hand anthropometry studies [15], in order to define the lengths for all phalanges and the relative positions of the finger base frames, concluding to a more humanlike design. Such a choice was made based on the hypothesis that if we design even our simple robot hands as anthropomorphically as possible, we will maximize their ability to grasp objects created for the human hand. For our design we have used identical robot fingers following the dimensions of human index finger. A future direction of ours is to formulate an optimization problem that will incorporate the metric proposed in [14], considering also other optimization schemes for robot hands design, proposed over the last years [16]–[18] and [19].

B. Compliant Flexure Joints and Soft Fingertips

Our main goal was to provide a design with the ability to stably grasp a wide range of objects, while keeping it simple, low cost and lightweight. In order to achieve this, we were based on conclusions extracted by recent works on the design of underactuated hands. More specifically, it has been shown that mounting compliant joints on the fingers, adds adaptability to the mechanism and thus leads to more robust and stable behavior, even when attempting to grasp objects with complex shapes [8]. Besides, soft materials are more preferred for designing the fingertips, as their deformation during contact, leads to larger contact areas, which reduce the impact of contact forces to the grasped object and also enhance stability [20]. Both conclusions can also be verified by our everyday life experience; the human hand, the most perfect end-effector known, can be characterized by high joint compliance and soft fingertips.

Motivated by the previous conclusions, we carefully selected the materials for the joints and the fingertips so that they satisfy our specifications. We made a compromise between affordable cost, lightweight design, high force transmission and adaptability. More specifically, the motion of the fingers in our grippers is implemented through flexure joints as a result of the compliance requirement. The flexible material (silicone and polyurethane sheets were considered) on the joints was selected to be lightweight but also stiff enough to be able to produce a force range, that corresponds to everyday life grasping tasks. Thus our robot hands demonstrate a sufficient ability of force transmission, without compromising deformability/adaptability.

As for the fingertips, a combination of sponge-like tape and low-thickness rubber (soft materials), was attached at them to increase also friction. This latter choice was made based on the study presented in [21], where various soft materials are used and compared in order to conclude which one is the best choice for the fingertips of robot hands (sponge-like materials).

The incorporation of these design decisions in the robot hands mechanisms can be described by existing models, proposed in recent literature. In particular, the behavior of flexure joints has been extensively studied by Odhner et al. [22], [23]. Their smooth curvature model is a computationally effective tool to predict the stiffness of such mechanisms so that real time closed loop control becomes possible. Currently, our ongoing research involves the incorporation of appropriate low-cost sensing elements for force measurements (at the fingertips) and joint-positions measurements, as well as of a control system implementing torque control policies in our robot hands, towards building a fully autonomous system. Finally, the behavior of soft materials at the fingertips, involving the force transmission at the contacts can be modeled with the *Soft Finger Model*, which is described in detail in [24].

C. A Modular Fingers Basis with Multiple Slots

In this section we present the modular fingers basis that is used for the creation of our robot hands. As it can be noticed in Fig. 2 and Fig. 3 the basis is equipped with 5 slots that can be used to accommodate a total of four fingers. Thus, robot hands with various geometries of finger base frames, can be developed. Line and 2D polytope geometries are easily created, while for 3D polytope geometries finger bases/connectors with different heights have to be used (to create vertical offsets). These hands are very capable of grasping various everyday life objects and each one is specialized for different types of tasks, executing in a more efficient manner the different grasp types presented in the various grasp taxonomies [25].

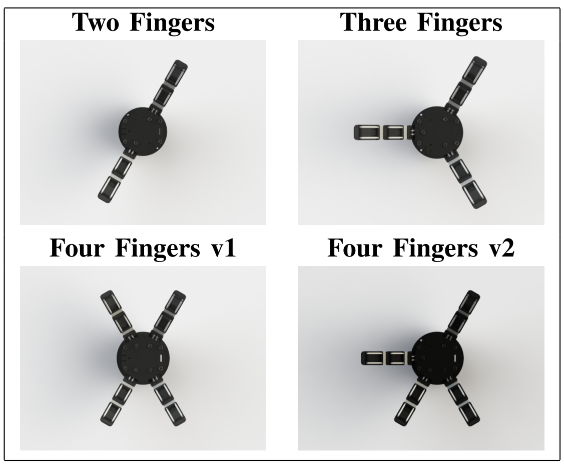

Fig. 2: Different robot hands created using identical modular fingers and the modular fingers basis. One two-fingered, one three-fingered and two versions of four-fingered robot hands, can be distinguished.

D. A Cross-Servo Modular Actuator Basis

The cross-servo modular actuator basis is a simple but yet effective design paradigm that lets the user of the robot hand to easily select and/or replace different types of servo motors. Appropriately designed slots are able to keep fixed most of commercially available servo motors, regardless of size and brand. For our robot hands four different types of servo motors have been considered, a micro servo with 2.2 kgr/cm torque for the aerial gripper (fixed at the front end of the Ar.Drone platform [26]), a standard servo with 12 kgr/cm torque, a Dynamixel AX-12A with 15.2 kgr/cm torque and the HerculeX DRS0201 with 24 kgr/cm torque. Of course more sophisticated high-torque servos with torque control can be considered according to the specification of each study, improving also the performance of our robot hands in terms of maximum force applied at the fingertips (of course with the counter effect of increased cost and weight).

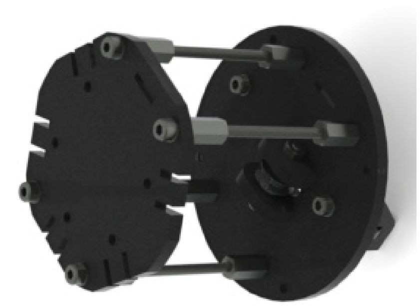

Fig. 3: The robot hands wrist module is depicted. The wrist module contains the fingers basis (left part of the photo) and the servo basis (right part of the photo).

E. A Disk-Shaped Differential Mechanism

A disk-shaped differential mechanism has been developed in order to connect the independent finger cables, with the actuator (servo motor). The differential mechanism allows for independent finger flexions, in case that one or multiple fingers have stopped moving, due to workspace constraints or in case that some fingers are already in contact with the object surface. Our differential mechanism is a variant of the whiffle tree (or seesaw) mechanism, inspired by the interesting work done in [27], where force analysis of connected differential mechanisms was conducted. More specifically in this latter study, authors analyze the concept of underactuation, presenting different categories and discussing appropriate techniques for developing differential mechanisms. A similar triangle-shaped differential mechanism can be found in [28]. An example of the differential mechanism operation, can be found in the accompanying video.

Fig. 4: The disk-shaped differential mechanism used.

F. Off-the-Shelf Low-Cost Parts

In Fig. 5 and Table I the different components selected for the development of the proposed robot hands are presented. As it can be noticed, all components are created using off-the-shelf, low-cost materials that can be easily found in hardware stores. For example the low-friction tubes can be substituted by common swabs (used for ear cleaning) by removing the parts covered with cotton. Plexiglas (acrylic) has been chosen as the main material for our design for the following reasons: it is low-cost, light-weight, it can be easily found, it has good durability, significant ultimate tensile strength (8.500 - 11.250 psi) and almost the same density (1.19 gr / cubic cm - 0.043 lbs / cubic inch), with other common plastics like ABS. Plexiglas can be cut with laser cutting machines or other machinery (even with hand-held rotary tools), that can be easily found, in contrary (at least for now) with 3D printers proposed by other design paradigms [8]. It must be noted that the hereby proposed design can be implemented with any kind of plastic or other material available and of course with the desired dimensions.

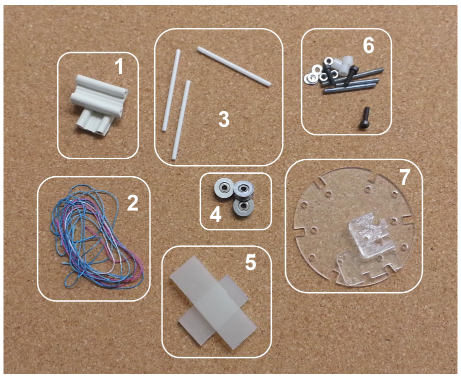

Fig. 5: The parts used for the creation of our robot hands are depicted. More details can be found in Table I.

TABLE I: Parts used for robot hands assembly

Number	Material	Characteristics
1	sponge-like tape	width: 1.8 mm
2	Dyneema fishing line	strength: 41.5kg (91.5 lb)
3	low friction tubes	d: 2 mm D: 2.5mm
4	pulleys	d: 3mm, D:12mm, W: 4mm
5	silicone sheets	3 mm - 4 mm
6	fasteners	width: 3mm
7	Plexiglas sheets	2 mm - 4 mm

G. Electronics, Codes and Communication

In order to control the servo motor that actuates the robot hand we use as low-cost, light-weight and small-sized solution the Arduino Micro platform [29]. In case that the robot hand is meant to be used as a myoelectric prosthesis, an appropriate low-cost surface Electromyography (sEMG) sensing kit (Advancer Technologies) [30] compatible with the arduino platform, is used. A standard PCB module has been developed on purpose. The PCB connects the arduino platform, with the servo motor and other sensors (current sensor for motor, flex sensors, force sensors etc.).

The serial communication between our robot hands and the Planner PC is implemented with Robot Operating System (ROS). An appropriate OpenBionics ROS package, has been developed. The Planner PC runs two nodes, the client node and the service node. The client node, receives from the user the aperture value (0 when the hand is fully open and 1 when the hand is fully close). The service node, sends the desired aperture to the robot hand. All codes are written in Python.

III. Results and Possible Applications

In this section we present a series of robot hands created with the proposed design. The ratio between the two angles for a robot finger with two phalanges, as well as the finger workspace, are depicted in Fig. 6.

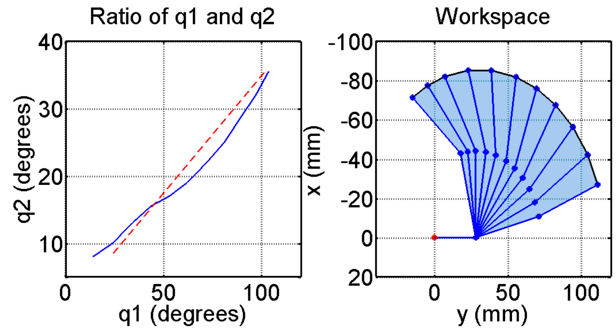

Fig. 6: The left subfigure presents the evolution of the ratio between the two angles, of a robot finger with two phalanges. The ratio approximates a constant value (red dotted line). The right subfigures presents the finger workspace.

The maximum force applied (and retained) per fingertip with the standard servo used, is 6 N for the three-phalanges humanlike robot finger and 8 N with the two phalanges robot finger. It must be noted that the maximum force depends not only on the servo used, but also on the quality and the thickness of the elastomer materials, thus the nominal values can also be adjusted according to the specifications of each study. In Fig. 7, we present different force exertion experiments for a single finger in different configurations.

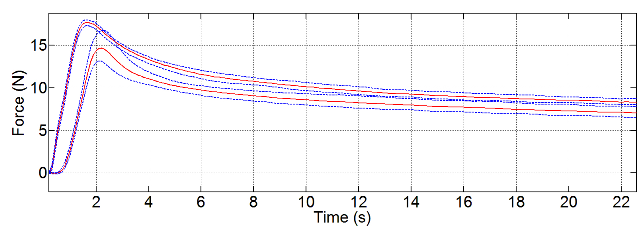

Fig. 7: Force exertion experiments for a two-phalanges robot finger at two different configurations (30% and 70% flexed). For each configuration, multiple experiments where conducted. The red lines represent the mean values and the blue dotted lines the min and max values per configuration. The high forces values correspond to the 30% flexed case and reach 18 N (peak), with a standard servo.

Regarding the robot hands, an aerial gripper, a two-fingered robot hand, two three-fingered robot hands and a four fingered, were created. All robot hands prototypes are depicted in Fig. 8. Due to the light-weight materials that are used in this design, the total weight of the robot hands remains low for all robot hand types. For example the aerial gripper's weight is 40 gr (0.088 lb), the two-fingered robot hand's weight is 120 gr (0.26 lb), the three fingered robot hand's weight is 180 gr (0.40 lb) and the four fingered robot hand's weight is 240 gr (0.53 lb), including for all cases the servos and the arduino platform.

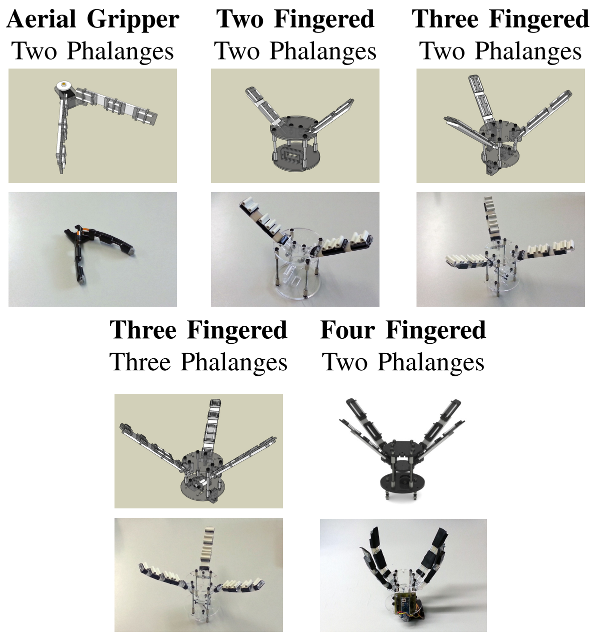

Fig. 8: Different robot hand models and robot hands created with the design directions provided, are depicted.

A. Autonomous Grasping and Telemanipulation Studies

Regarding possible applications, the proposed open source design, can be used by research groups around the world, to create low-cost robot hands for autonomous grasping or teleoperation/telemanipulation studies. For example our lab is equipped with the DLR/HIT II robot hand [31], which costs approximately 80.000 USD (of course this price covers also development and manufacturing time, personnel costs etc.) and has a maximum aperture of approximately 7cm failing to grasp numerous everyday life objects and marginally grasping a 500 ml bottle of water. For the 1/1000 of this cost one can have a custom made robot hand, according to the specifications of the task to be executed, able to grasp a plethora of everyday life objects (even with large diameters).

B. Creating Mobile and Aerial Grasping Capable Platforms

Another possible application for our robot hands is to be integrated in several aerial and mobile platforms to replace simple grippers with limited grasping capabilities. Examples of such platforms are the Baxter (Rethink Robotics) [1] and the YouBots mobile platform (KUKA) [2]. Moreover their light-weight design makes them the ideal choice for creating aerial grippers, than can be easily incorporated even in non-sophisticated aerial vehicles like the Ar.Drone quadrotor platform [26].

C. Towards Low-Cost Task-Specific Myoelectric Prostheses

The idea of low-cost, light-weight prostheses is not a new one [32]. A recent work [33], focused on the findings of multiple studies on upper limb myoelectric prostheses as well as on the comments, suggestions and remarks made by amputees for their prosthetic hands. The subjects of these studies expressed their disappointment for the large initial and maintenance costs of the prostheses, the weight of the prostheses and the difficulties they face with repairs. Moreover the same studies, showed that the involvement of the amputee in the selection of a prosthesis increased 8 times the likelihood of prosthesis acceptance and that the fear of damage, leads most amputees to avoid to use them in everyday life tasks and use instead simple hooks or grippers, which are reported to have high functional value. Finally it was also reported that an important attribute for amputees, is the prostheses to enable specific motor actions (e.g., for hobbies, driving/cycling, work etc.), in other words to be optimized for specific tasks. Thus our low-cost, light-weight design can be used by millions of amputees around the world (especially amputees from third world countries), which can benefit from the DIY tutorials that we will provide, in order to build personalized, affordable, even task-specific myoelectric prostheses.

D. Videos of Experiments

In Fig. 8 the different types of robot hands are depicted both using their 3D models as well as pictures of the actual robot hands developed. In the following video, we present extensive experimental paradigms with two fingered, three fingered and four fingered robot hands. It must be noted, that for all experiments conducted the standard servo was used, in order for the total cost of the hands created to remain below 100 USD. More specifically at the first part of the video we grasp everyday life objects with a four-fingered (each finger consists of two phalanges) robot hand. At the second part of the video, a three fingered robot hand is used as a myoelectric prosthesis (by an able-bodied person) and the subject grasps using the myoelectric activity of his forearm muscles, two different objects. The third part of the video presents some preliminary results on a grasping capable quadrotor (based on the AR.Drone platform [26]) that we created in our lab using a two-fingered robot hand prototype. The forth part presents an example of the operation of the disk shaped differential mechanism. The fifth part presents a robot hand grasping a full 500ml bottle of water with a lateral pinch grasp, while the sixth part presents a precision grasp of an egg. Details on EMG signals pre-processing and EMG-based interfaces can be found in [34]. The video (in HD) can be found at:

`http://www.youtube.com/watch?v=yEANsfaE1gs`

The second video presents, an experimental validation of the efficiency of the proposed robot hands for the case of autonomous grasping. More specifically Navigation Function based models are learned for moving the Mitsubishi PA10 7 DoFs robot arm in an anthropomorphic manner, while a four fingered robot hand with two phalanges per finger (attached at the end-effector of the robot arm), is developed on purpose. As it can be seen the robot hand efficiently grasps a series of everyday life objects, even if their position and/or shape are not accurately known/predefined (in case of uncertainties).

`http://www.youtube.com/watch?v=xs2CC9QLuFc`

The third video presents the Grebenstein test, that we use to test our robot hands robustness again impacts.

`http://www.youtube.com/watch?v=bniHWeXpX0A`

The OpenBionics open-source initiative [35] website, has been created to provide tutorials, designs and codes for the replication of our robot hands:

`http://www.openbionics.org`

OpenBionics is inspired by the open hand project [36] of Grab Lab (Yale University).

IV. Conclusions and Discussion

In this paper we presented a series of design directions for the development of low-cost, light-weight, intrinsically-compliant, modular robot hands, that can be easily reproduced using common, off-the-shelf materials. The hands proposed are general purpose, as they can be used for various applications and are capable of grasping a plethora of everyday life objects. Extensive experimental paradigms with different types of robot hands are presented, to prove the efficiency of the proposed design and the significant grasping capabilities of our hands.

References

[1] R. Robotics, "Baxter," 2013. [Online]. Available: http://www.rethinkrobotics.com/

[2] KUKA, "Youbots," http://www.youbot-store.com/, 2013.

[3] M. Grebenstein, A. Albu-Schaffer, T. Bahls, M. Chalon, O. Eiberger, W. Friedl, R. Gruber, S. Haddadin, U. Hagn, R. Haslinger, H. Hoppner, S. Jorg, M. Nickl, A. Nothhelfer, F. Petit, J. Reill, N. Seitz, T. Wimbock, S. Wolf, T. Wusthoff, and G. Hirzinger, "The dlr hand arm system," in *Robotics and Automation (ICRA), 2011 IEEE International Conference on*, may 2011, pp. 3175–3182.

[4] L. Birglen, T. Lalibert, and C. M. Gosselin, *Underactuated Robotic Hands*, ser. Springer Tracts in Advanced Robotics. Springer, 2008, vol. 40.

[5] R. R. Ma, L. U. Odhner, and A. M. Dollar, "A modular, open-source 3d printed underactuated hand," in *Robotics and Automation (ICRA), 2013 IEEE International Conference on*, may 2013.

[6] F. Lotti, P. Tiezzi, G. Vassura, L. Biagiotti, G. Palli, and C. Melchiorri, "Development of ub hand 3: Early results," in *Robotics and Automation, 2005. ICRA 2005. Proceedings of the 2005 IEEE International Conference on*, 2005, pp. 4488–4493.

[7] R. Deimel and O. Brock, "A compliant hand based on a novel pneumatic actuator," in *IEEE International Conference on Robotics and Automation (ICRA)*, May 2013, pp. 2047–2053.

[8] A. Dollar and R. Howe, "A robust compliant grasper via shape deposition manufacturing," *Mechatronics, IEEE/ASME Transactions on*, vol. 11, no. 2, pp. 154–161, 2006.

[9] A. M. Dollar and R. D. Howe, "The highly adaptive sdm hand: Design and performance evaluation," *Int. J. Rob. Res.*, vol. 29, no. 5, pp. 585–597, Apr. 2010.

[10] L. Wang, J. DelPreto, S. Bhattacharyya, J. Weisz, and P. K. Allen, "A highly-underactuated robotic hand with force and joint angle sensors," in *Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on*, 2011, pp. 1380–1385.

[11] V. Tincani, M. Catalano, E. Farnioli, M. Garabini, G. Grioli, G. Fantoni, and A. Bicchi, "Velvet fingers: A dexterous gripper with active surfaces," in *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*, 2012, pp. 1257–1263.

[12] L. Odhner, L. P. Jentoft, M. R. Claffee, N. Corson, Y. Tenzer, R. R. Ma, M. Buehler, R. Kohout, R. D. Howe, and A. M. Dollar, "A compliant, underactuated hand for robust manipulation," *CoRR*, vol. abs/1301.4394, 2013.

[13] Meka, "H2 compliant hand," 2009. [Online]. Available: http://mekabot.com/products/compliant-hand/

[14] M. V. Liarokapis, P. K. Artemiadis, and K. J. Kyriakopoulos, "Quantifying anthropomorphism of robot hands," in *IEEE International Conference on Robotics and Automation (ICRA)*, May 2013.

[15] B. Buchholz, T. J. Armstrong, and S. A. Goldstein, "Anthropometric data for describing the kinematics of the human hand." *Ergonomics*, vol. 35, no. 3, pp. 261–73, 1992.

[16] A. M. Dollar and R. D. Howe, "Towards grasping in unstructured environments: grasper compliance and configuration optimization," *Advanced Robotics*, vol. 19, no. 5, pp. 523–543, Jun. 2005.

[17] M. Ciocarlie and P. Allen, "Data-driven optimization for underactuated robotic hands," in *Robotics and Automation (ICRA), 2010 IEEE International Conference on*, 2010, pp. 1292–1299.

[18] F. Hammond, J. Weisz, A. de la Llera Kurth, P. K. Allen, and R. Howe, "Towards a design optimization method for reducing the mechanical complexity of underactuated robotic hands," in *Robotics and Automation (ICRA), 2012 IEEE International Conference on*, 2012, pp. 2843–2850.

[19] C. I. Mavrogiannis, C. P. Bechlioulis, M. V. Liarokapis, and K. J. Kyriakopoulos, "Task-specific grasp selection for underactuated hands," in *IEEE International Conference on Robotics and Automation (ICRA)*, 2014.

[20] M. T. Ciocarlie, A. T. Miller, and P. K. Allen, "Grasp analysis using deformable fingers." in *IROS*. IEEE, 2005, pp. 4122–4128.

[21] K. Shimoga and A. Goldenberg, "Soft materials for robotic fingers," in *Robotics and Automation, 1992. Proceedings., 1992 IEEE International Conference on*, 1992, pp. 1300–1305 vol.2.

[22] L. Odhner and A. M. Dollar, "The smooth curvature flexure model: An accurate, low-dimensional approach for robot analysis." in *Robotics: Science and Systems*, Y. Matsuoka, H. F. Durrant-Whyte, and J. Neira, Eds. The MIT Press, 2010.

[23] L. Odhner and A. Dollar, "The smooth curvature model: An efficient representation of euler bernoulli flexures as robot joints," *Robotics, IEEE Transactions on*, vol. 28, no. 4, pp. 761–772, 2012.

[24] B. Siciliano and O. Khatib, *Springer Handbook of Robotics*, ser. Gale virtual reference library. Springer, 2008.

[25] M. Cutkosky, "On grasp choice, grasp models, and the design of hands for manufacturing tasks," *Robotics and Automation, IEEE Transactions on*, vol. 5, no. 3, pp. 269–279, 1989.

[26] Parrot, "Ar.drone 2 quadrotor," http://ardrone2.parrot.com/, 2013.

[27] L. Birglen and C. M. Gosselin, "Force analysis of connected differential mechanisms: Application to grasping," *The International Journal of Robotics Research*, vol. 25, no. 10, pp. 1033–1046, 2006.

[28] J. L. Herder and H. de Visser, "Force directed design of a voluntary closing hand prosthesis," in *DETC 2000 : 2000 ASME Design Engineering Technical Conference*, no. MECH-14149, Sep. 2000, pp. 1–8.

[29] Arduino, "Open-source electronics prototyping platform based on microcontroller," http://www.arduino.cc, Feb. 2013.

[30] A. Technologies, "Muscle sensor v3," http://www.advancertechnologies.com/, 2013.

[31] H. Liu, K. Wu, P. Meusel, N. Seitz, G. Hirzinger, M. Jin, Y. Liu, S. Fan, T. Lan, and Z. Chen, "Multisensory five-finger dexterous hand: The DLR/HIT Hand II," in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Sept 2008, pp. 3692–3697.

[32] R. Doshi, C. Yeh, and M. LeBlanc, "The design and development of a gloveless endoskeletal prosthetic hand," *Journal of Rehabilitation Research & Development*, vol. 35, no. 4, p. 388, 1998.

[33] D. Edeer and C. W. Martin, "Upper limb prostheses - a review of the literature with a focus on myoelectric hands," 2013. [Online]. Available: www.worksafebc.com/evidence

[34] M. Liarokapis, P. Artemiadis, K. Kyriakopoulos, and E. Manolakos, "A learning scheme for reach to grasp movements: On EMG-based interfaces using task specific motion decoding models," *Biomedical and Health Informatics, IEEE Journal of*, vol. 17, no. 5, pp. 915–921, 2013.

[35] M. V. Liarokapis, A. G. Zisimatos, C. I. Mavrogiannis, and K. J. Kyriakopoulos, "Openbionics: An open-source initiative for the creation of affordable, modular, light-weight, underactuated robot hands and prosthetic devices," in *2nd ASU Rehabilitation Robotics Workshop*, February 2014. [Online]. Available: http://www.openbionics.org

[36] Y. U. Grab Lab, "Yale openhand project," 2013. [Online]. Available: http://www.eng.yale.edu/grablab/openhand/