A Low-Cost Open-Source 3-D-Printed Three-Finger Gripper Platform for Research and Educational Purposes

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ABSTRACT Robotics research and education have gained significant attention in recent years due to increased development and commercial deployment of industrial and service robots. A majority of researchers working on robot grasping and object manipulation tend to utilize commercially available robot-manipulators equipped with various end effectors for experimental studies. However, commercially available robotic grippers are often expensive and are not easy to modify for specific purposes. To extend the choice of robotic end effectors freely available to researchers and educators, we present an open-source low-cost three-finger robotic gripper platform for research and educational purposes. The 3-D design model of the gripper is presented and manufactured with a minimal number of 3-D-printed components and an off-the-shelf servo actuator. An underactuated finger and gear train mechanism, with an overall gripper assembly design, are described in detail, followed by illustrations and a discussion of the gripper grasping performance and possible gripper platform modifications. The presented open-source gripper platform computer-aided design model is released for downloading on the authors research lab website (www.alaris.kz) and can be utilized by robotics researchers and educators as a design platform to build their own robotic end effector solutions for research and educational purposes.

INDEX TERMS Open-source robotic gripper, gear train mechanism, 3D printing, underactuation, adaptive grasping.

I. INTRODUCTION

The 3D printing has been widely recognised as a valuable and efficient technology for low-cost manufacturing of custom research and educational equipment. Due to the ability to manufacture various 3D object designs from CAD models in relatively short time with minimum cost and efforts, [1]–[3]. Using 3D-printed prototypes, researchers and educators can benefit from lower expenditures, easier equipment maintenance and repair, better availability of spare parts, higher relevance and flexibility of adaptation to research needs and education curriculum [4].

Among vast robotics research directions, academic research on robotic grasping and object manipulation have gained significant attention in recent years due to the increased development and commercial deployment of industrial and service robots [5]–[8]. However,

majority of researchers working in this direction do not have mechanical engineering background and, hence, tend to utilize commercially available robot-manipulators equipped with various end effectors for experimental studies. Anthropomorphic robotic hands are widely used for research related to human like grasping and object manipulation where reproducing the human hand functionality is required [8]–[12]. On the other hand, three-finger grippers with relatively simple designs are sufficient to conduct research activity and educational process on manipulation of objects in industrial and service applications [6], [13]. Examples of such gripper designs are a three-finger concentric gripper [14] designed for relatively high payload industrial applications, a reconfigurable gripper [15] with convex shape thin fingers designed for picking and placing round objects, and an adaptive three-finger robot

gripper [16] for use in unstructured industrial applications. A lot of end effector designs utilize individual actuation of each joint of the fingers with small high precision DC servomotors [17], [18]. This ensures a high number of controllable degrees of freedom (DOF) suitable for grasping of complex shape objects. However, the presence of multiple actuators in each finger mechanism results in high cost and control complexity of a gripper.

In general, many of the commercially available robotic end effectors do not accommodate extensive customisation of the design features for attachment to different robotic arm platforms or integration of additional sensors for research and educational purposes [19]. Moreover, very high purchase and maintenance costs of the commercial robotic end effectors prevent their purchase by academic institutions, especially in developing countries. In this respect, the 3D printing rapid prototyping technology offers the way to produce low-cost robotic end effectors [12], [19], [20] that can be used in research and education [21]. This is facilitated by providing open-source computer-aided design (CAD) models of the end effectors that can be straightforwardly prototyped using a low-cost desktop 3D printer and assembled with off-the-shelf components. For instance, a 3D-printed open-source tendon driven hand is proposed in [19] aiming to provide a basic robotic platform with minimal number of 3D-printed components and off-the-shelf actuator for facilitating robotic research efforts. In fact, open-source developmental methods already provide alternative to expensive and proprietary software packages, and gradually spread to other areas such as engineering research and education [3].

To extend the choice of robotic end effectors freely available to researchers, in this paper the authors utilize a linkage based finger design and propose a low-cost open-source 3D-printed underactuated three-finger robotic gripper platform with a simple design and relatively higher payload property comparing to similar size tendon driven mechanisms [22]. The proposed design of the gripper platform can be easily customized and extended for use in various research and educational projects. The 3D model of the gripper has been created using SolidWorks CAD software and is available for downloading from the authors' research lab web-site (www.alaris.kz).

The organization of the paper is as follows. Section II describes the design and prototype assembly of the three-finger robotic gripper including underactuated finger and gear train design and analysis. The grasping performance of the gripper prototype is presented in Section III, which is followed by the discussion on possible design modifications and conclusion in Sections IV and V, respectively.

II. DESIGN OF A 3D-PRINTED THREE FINGER GRIPPER
A. FINGER DESIGN
As previously discussed, low cost is one of the principal design requirements for the developed robotic gripper.

To fulfill this requirement, the authors have maximized the usage of off-the-shelf components as well as making most of the gripper structure suitable for prototyping on a low-cost 3D printer.

In addition, the low cost design requirement also imposes a hard constraint on minimizing the number of actuators and control electronics, that would, in turn, lead to reducing of the end effector size and mass. This can be achieved by coupling the motion of numerous joints, leading to the design with fewer actuators than degrees of freedom. Such robotic end effectors, i.e. robotic hands or grippers, termed *underactuated*, have shown significant advantages in grasping applications due to the passive flexibility and adaptability between degrees of freedom. This is largely attributed to the relatively simple design of the finger mechanisms comparing with fully actuated dexterous artificial fingers [24]. At the same time, an underactuated finger design should ensure close wrapping of different shape objects due to its adaptive grasping capability with one DOF actuation.

A number of the underactuated designs utilize pulley/tendon driven mechanisms for wide range of robotics systems [25]. They have many advantages such as low weight, less number of actuators and high degree of adaptability. Among disadvantages are limitations in load carrying capacity and low wear resistance, especially often appearing in 3D-printed prototypes. Therefore, as an alternative, mechanical linkage systems have been utilized for different designs of underactuated artificial fingers [16], [26].
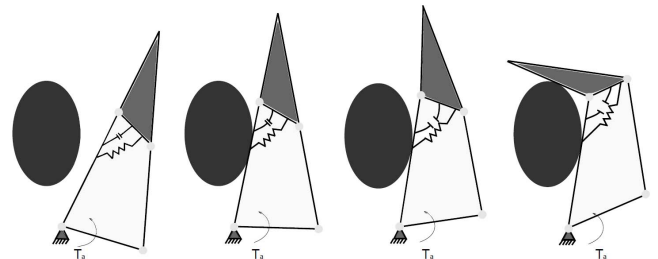

FIGURE 1. Closing sequence of a 2-DOF underactuated finger [23].

In this work, the authors adopted the underactuated gripper finger design presented in [23] and [27]. The design utilizes a simple mechanical linkage system which is the one of the main design objectives for the proposed open-source gripper. Consider a 2-DOF and one degree-of-actuation finger mechanism shown in Fig.1. A passive element, i.e. a spring, between the first and second phalanges is used for providing actuation of the second DOF of the finger [23]. The closing sequence of the underactuated finger is described as follows. Firstly, the finger moves as a rigid body from its initial position since no external force is acting on it. When the first phalanx of the finger is in contact with an object, the second phalanx starts movement around a pivot point to complete a full wrapping. Same method can be applied to n-phalanx finger [23]. However, accurate finger mechanism
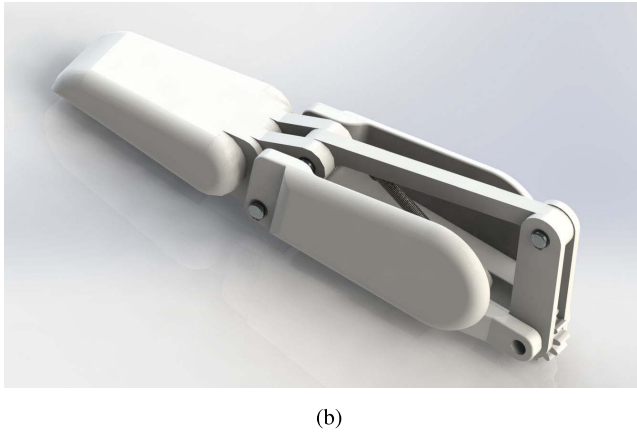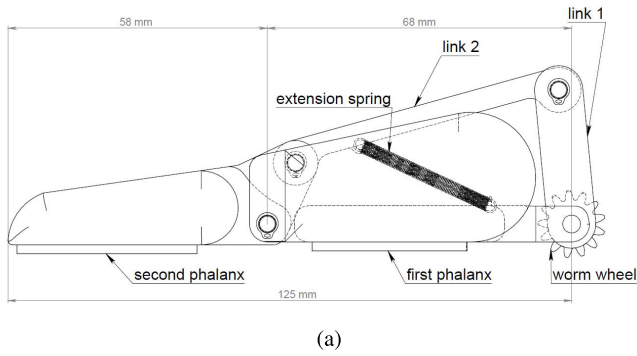
FIGURE 2. 2D (a) and 3D (b) designs of the underactuated finger.

analysis is required to calculate parameters for the passive elements.

Utilizing the same principle, an underactuated finger mechanism has been designed using SolidWorks CAD software and is presented in Fig. 2. The finger consists of two phalanges, two links, an extension spring and a worm wheel. Note that the worm wheel and link 1 are rigidly connected. The worm wheel transmits rotary motion to link 1 around its pivot point; subsequently link 1 transfers the motion to link 2. The extension spring, shown in Fig. 2(a), allows the finger to behave as a single rigid body during rotary motion around the fixed pivot. When the first phalanx touches an object, the force produced by an actuator extends the spring which starts transferring motion to the second phalanx only. Finally, the contact of both the phalanges with an object concludes the finger closing sequence.

The surfaces of the finger components are flat so that the printer support material can be removed manually without great effort. All rotational joints of the finger are connected via pivots with retaining rings at both sides, as shown in Fig. 2(b). The pivot 3D models are supplied with the gripper CAD model in the open-source gripper package and can be used for manufacturing metal pivots using standard machine shop facilities.

B. FINGER ANALYSIS

Grasping characteristics of the gripper can be modified by setting various geometries of two actuation links of
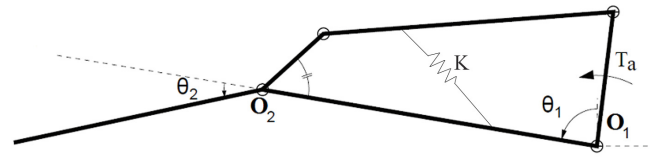

FIGURE 3. Schematic model of the 2-DOF underactuated finger.

the fingers. For instance, changing the length of two actuation links of the finger can result in various dynamic outputs of the first and second phalanges.

Selection of an appropriate spring stiffness coefficient K that defines actuation of the finger's second phalange is based on the kinematic analysis of the underactuated finger mechanism. The schematic model of the finger is presented in Fig. 3. The quasi-static equilibrium modelling of the finger is defined as follows. By equating the input and the output virtual powers [13], the following expression is derived

$$t^T \omega_a = f^T v, \quad (1)$$

where t is the input torque vector, ω_a is the velocity vector, f is the vector of contact wrenches, and v is the vector containing the twist of the contact points [28], defined as

$$t = \begin{bmatrix} T_a \\ T_2 = -K \triangle \theta_2 \end{bmatrix}; \quad \omega_a = \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix}; \quad (2)$$

$$f = \begin{bmatrix} \zeta_1 \circ \\ \zeta_2 \circ \end{bmatrix}; \quad v = \begin{bmatrix} \xi_1 \\ \xi_2 \end{bmatrix}. \quad (3)$$

Here, T_a denotes the actuation wrench, K is the spring stiffness, $\dot{\theta}_i$ is the first derivative of phalange $i = 1, 2$ joint angles. Row vectors $\zeta_i \circ = \begin{bmatrix} m_z & f_i^x & f_i^y \end{bmatrix}$ for $i = 1, 2$, are obtained from the corresponding three-dimensional wrench vectors $\zeta_i = \begin{bmatrix} f_i^x & f_i^y & m_z \end{bmatrix}$ by writing the moment m_z of the force axis about the platform center before the force unit vector $f_i = \begin{bmatrix} f_i^x & f_i^y \end{bmatrix}$ [29]. $\xi_i = \begin{bmatrix} \omega_z & \vartheta_i^x & \vartheta_i^y \end{bmatrix}$ is the three-dimensional vector for planar twist.

Substitution of eq. (2) and eq. (3) into eq. (1) yields

$$\begin{bmatrix} T_a & -K \triangle \theta_2 \end{bmatrix} \cdot \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} = \begin{bmatrix} \zeta_1 \circ & \zeta_2 \circ \end{bmatrix} \cdot \begin{bmatrix} \xi_1 \\ \xi_2 \end{bmatrix}, \quad (4)$$

from where by equating two matrices from each side the following equation is obtained

$$T_a \dot{\theta}_{a_1} - K \triangle \theta_2 \cdot \dot{\theta}_2 = \zeta_1 \circ \cdot \xi_1 + \zeta_2 \circ \cdot \xi_2 \quad (5)$$

Thus, the stiffness of the spring can be expressed as

$$K = \frac{T_a \dot{\theta}_1 - \zeta_1 \cdot \circ \xi_1 - \zeta_2 \circ \cdot \xi_2}{\triangle \theta_2 \cdot \dot{\theta}_2} \quad (6)$$

and is used to select appropriate spring for selected finger configuration defined mainly by the actuator characteristics T_a and desired fingertip rotational displacement $\triangle \theta_2$ and its derivative $\dot{\theta}_2$.
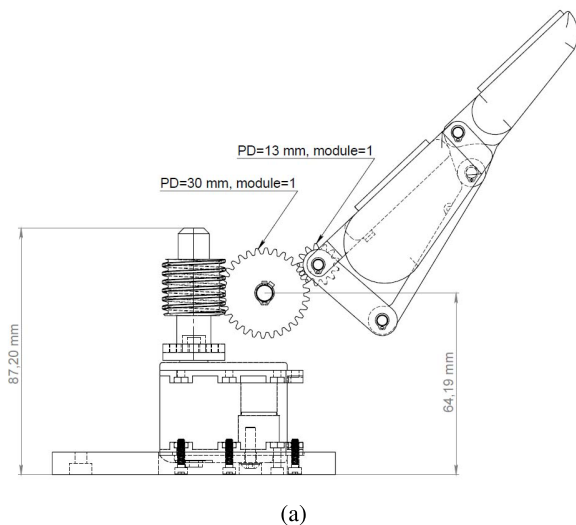
FIGURE 4. 2D (a) and 3D (b) sketches of the gear train design for one finger.

C. GEAR TRAIN DESIGN

The three fingers in the gripper are actuated by a single actuator using a gear train transmission system. The 2D and 3D representations of the single finger actuation is shown in Fig. 4. A servo actuator is fixed on the base and drives the directly connected worm gear. The worm transfers rotational motion to the set of worm wheels, which are connected to each finger.

All three fingers are driven simultaneously from their initial position. Usage of the worm gear ensures non-backdriveability of the finger actuation mechanism.

The set of two worm wheels are placed in a way that allows adjustment of the rotational speed and torque transferred to a finger by changing the gear ratios within the given distance between gear rotational axes. Researchers can also change the actuator and set up custom gear train speed/torque ratio depending on their need without modifying the overall gripper design.

Due to possible limitations in producing strong and precise miniature parts that can be caused by the low resolution of a low-cost desktop 3D printer and/or printing material properties, the gear train design utilizes a minimal number of small size parts. The worm gear and the worm wheels for the open-source gripper prototype are designed to allow easy manufacturing that is achieved with high gear tooth module number. However, it is possible to easily replace the present gears with different variants depending on custom gripper requirements. More advanced additive manufacturing technology or equipment, and/or of-the-shelf metal gear components can be used instead to design a more durable gear train with smaller gears if required.

D. GRIPPER ASSEMBLY

The presented three finger robotic gripper consists of the three 2-DOFs underactuated fingers, a base, a palm, a gear train set and an actuator. The fingers are attached in a circular way with 120 degrees between each other. This allows the worm wheels of the fingers to be driven from a single actuator via the actuating worm as illustrated in Fig. 5. This type of the finger placement is preferable for grasping spherical or cylindrical objects of different sizes.

The CAD model of the proposed open-source robotic gripper and its 3D-printed assembled prototype are presented in Fig. 6. The prototype main structures are manufactured using the UP Plus 3D printer [30] with acrylonitrile butadiene styrene (ABS) plastic, whereas soft rubber printing material are used for producing fingertip, phalange and palm covers. ABS is a strong, durable production-grade thermoplastic used across many industries, and it is an ideal material for conceptual prototyping [31]. An additional off-the-shelf component, a Dynamixel MX-28 servomotor [32], is used as an actuator for the robotic gripper prototype that eliminates necessity for complex electronic circuits and encoders implementing motor position control. Control of the servomotor can be performed directly from MATLAB or C/C++ programming environments as well as using the Robot Operating System (ROS) [33], that provide easy and straightforward integration of the gripper with other robotic research and educational setups. The output torque of the servomotor is 2.5 Nm at 12V power supply voltage.

The exploded assembly view of the gripper design is presented in Fig. 7. The actuator is mounted using bolts on a base with a circular shape and flat bottom. The base shape and attachment holes for mounting the gripper can be further created in a CAD program or easily drilled depending on robotic arm used. The worm is fixed to the actuator's output
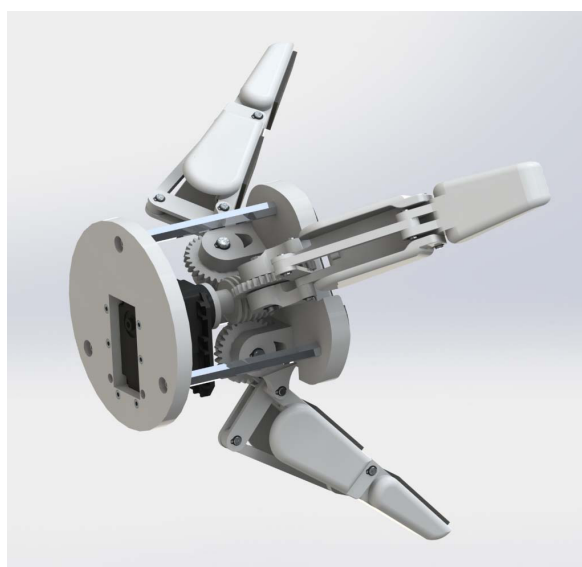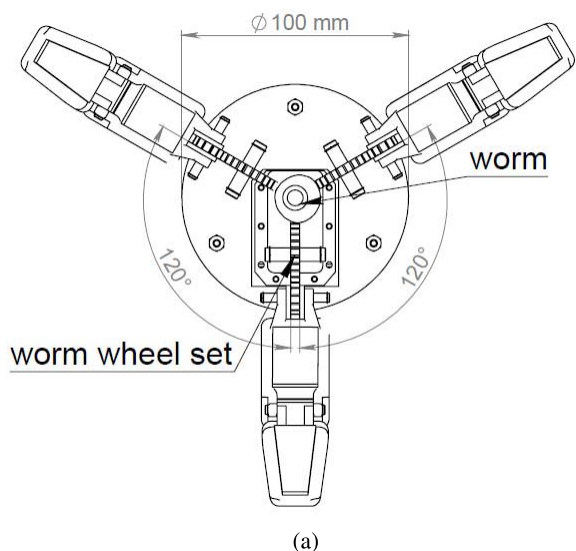
(a)

(b)

FIGURE 5. Arrangement of worm wheels connected to the actuating worm in 2D (a) and 3D (b) views.

TABLE 1. Bill of materials for the open-source 3D-printed gripper.

Item	Source	Quantity	Total Cost
Short link	3D-printed	3	$0.30
Palm	3D-printed	1	$3.20
Long link	3D-printed	3	$0.30
Finger tip	3D-printed	3	$2.40
Proximal phalange	3D-printed	3	$2.40
Standoff	VEX Robotics	3	$8.00
Worm wheel	3D-printed	3	$0.32
Worm	3D-printed	1	$0.40
Base	3D-printed	1	$2.10
Dynamixel actuator	Robotis	1	$219.90
Shaft for worm wheel	Metallic shaft	3	$3.00
Shaft at PIP	Metallic shafts	3	$3.00
Shaft at MCP	Metallic shafts	3	$3.00
Shaft for link	Metallic shafts	3	$3.00
Shaft for long link and finger tip	Metallic shafts	3	$3.00
Top and bottom screw	WURTH	6	$6.00
M2.5 screw for actuator	WURTH	6	$3.00
M2.5 nut for actuator	WURTH	6	$0.6
Rubber cover for palm	3D-printed	1	$4.00
Rubber cover for phalange	3D-printed	3	$1.50
Rubber cover for fingertip	3D-printed	3	$1.50
Small retaining ring	WURTH	24	$16.8
Big retaining ring	WURTH	6	$4.2
Bearing	sdp-si.com	6	$30.00
Spring	sdp-si.com	3	$6.00
		Overall	**$327.92**

shaft at one side and to the palm at the other end. The worm axis is coincident with the symmetry axis of the gripper palm. The three fingers are fixed to the palm via pivots (shafts) with retaining rings and rotate about their pivot points. The palm and the base are connected to each other via three aluminium standoffs fixed by bolts from both sides. The standoffs with various length can be used to accommodate alternative gear trains. The palm and the fingers have spacings for thin rubber cushions. These outer cushions are designed for reducing slippery between the gripper and a grasping object and can be 3D-printed using any rubber-like material. If needed, the cushions can be replaced by tactile sensors with minor modification of the finger and palm designs. The overall weight of the gripper with current configuration is 500 grams.

The bill of materials for the gripper is given in Table 1. It includes the list of the gripper elements with quantity, cost and source information needed to estimate the overall cost of the gripper prototype. Rough calculations show that the overall cost of the gripper prototype should not exceed USD $400 which makes the gripper manufacturing very attractive in terms of the cost comparing to similar commercial grippers with the price of about several thousands USD. The 3D-printed part's cost is calculated in accordance with their weight. All calculations in Table 1 are made with assumption that one kilogram of the ABS plastic costs about USD $40. Recent development of desktop 3D printers like the used UP Plus 3D printer [30] with the
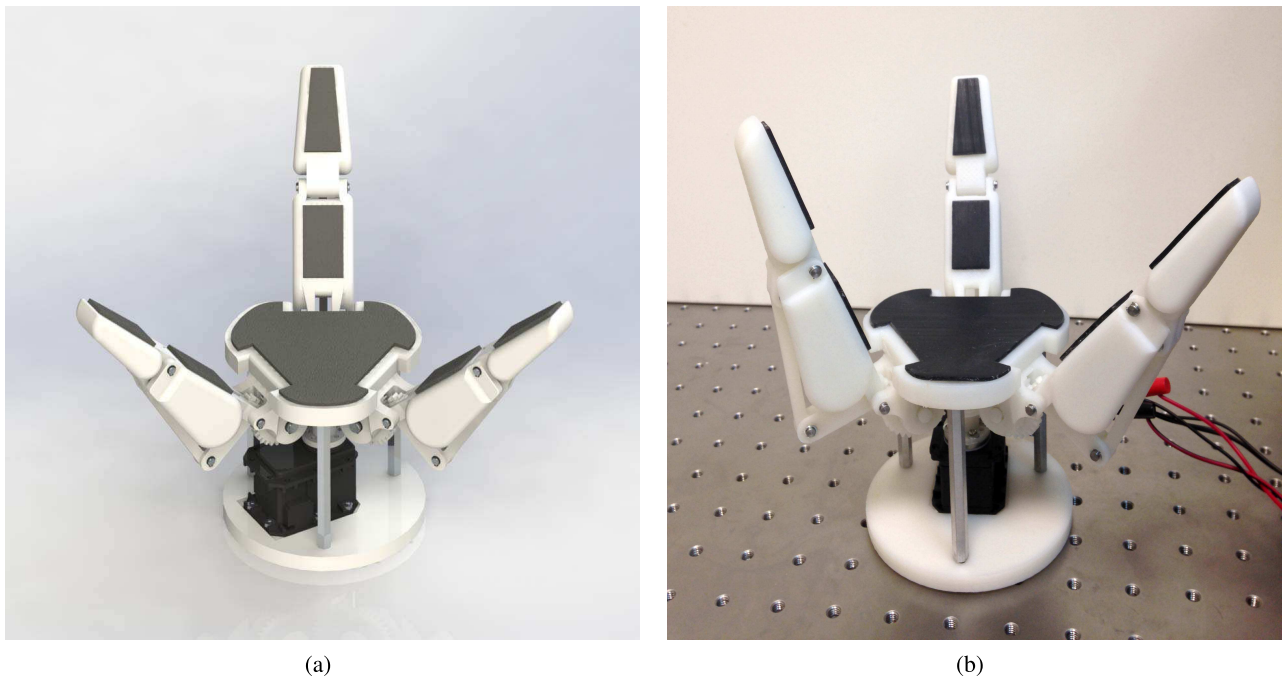
FIGURE 6. Three finger gripper CAD assembly model (a) and its 3D-printed prototype (b).
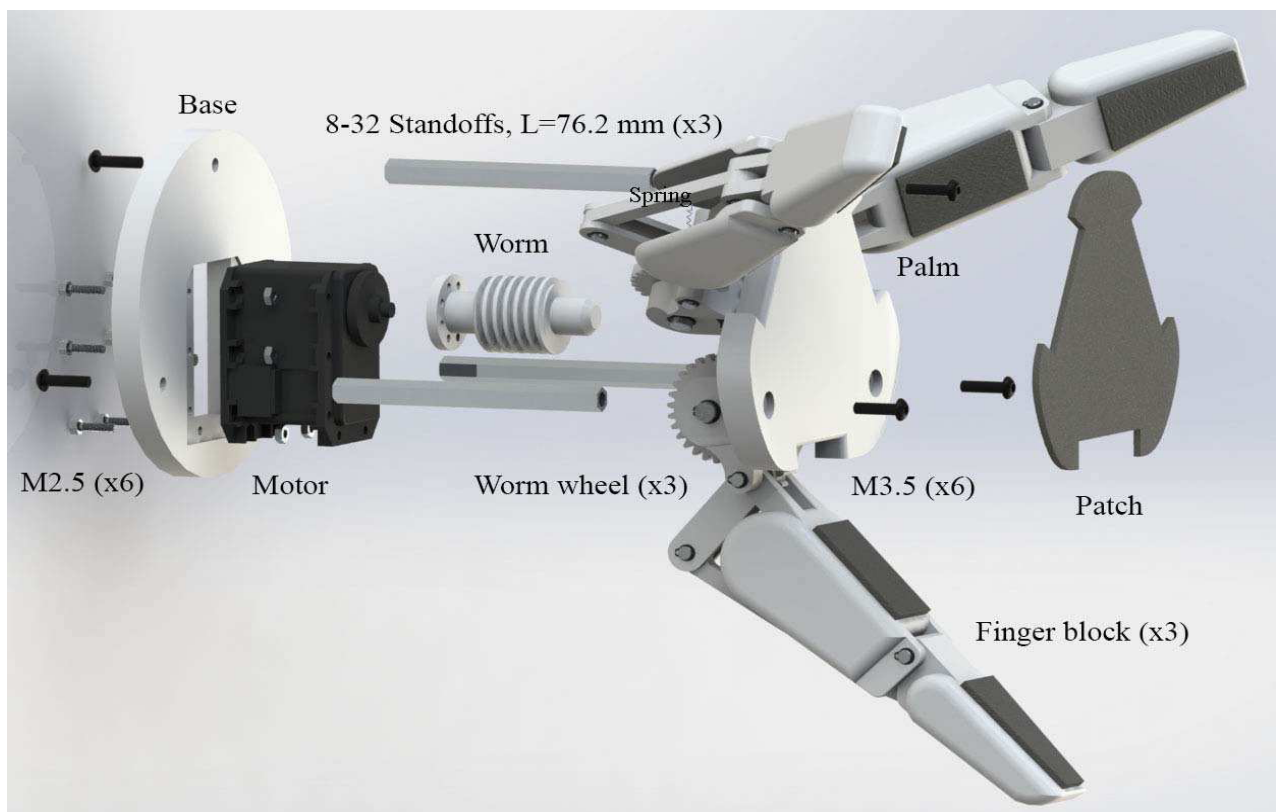

FIGURE 7. Exploded assembly view of the open-source three-finger gripper.

price less than USD $1700 [30], make the overall cost of setting up basic rapid prototyping facilities accessible to most academic institutions [4]. The metallic shafts are produced at machine shop using turning and milling machines. Actuator, screws, nuts and standoff are commercially available at manufacturer web-sites and can be easily purchased.
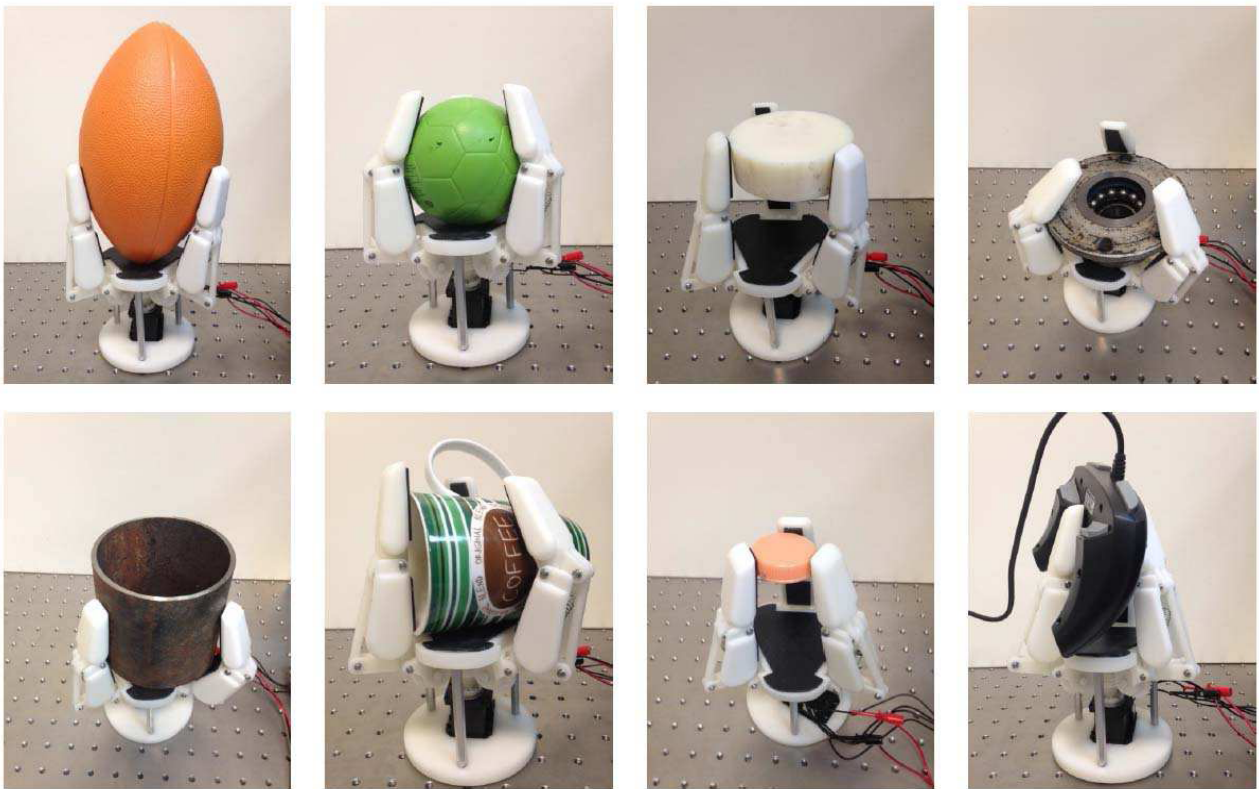
FIGURE 8. Grasping of different objects using the open-source 3D-printed gripper prototype.

III. GRASPING PERFORMANCE

The effective grasping of objects with different shapes and sizes is one of the important gripper design requirements. The proposed 3D-printed gripper prototype ensures adaptive passive grasping and full wrapping of grasping objects. Figure 8 illustrates the performance of the gripper in grasping a number of objects with different shapes. As shown in the figure during the grasping of an egg shaped ball all the three gripper fingers and their phalanges move as single rigid bodies and their passive elements are not active.

On the other hand, the springs in each finger provide the second DOF when grasping a spherical shaped ball: as all the first phalanges of the fingers touch the ball, the second phalanges envelop the object and complete grasping. The same grasping pattern is observed in grasping short cylindrical objects such as a bearing block.

Small objects are normally grasped by second phalanges or finger tips only, performing the spherical pinch grasp.

Executing grasping of complex shape objects with strong asymmetric geometry, all the three fingers wrap of the object with different degree of bending depending on the object shape. For example, in the case of grasping of a cup and a joystick objects, one finger moves as a single rigid body while the others actuate the second DOF and envelop the object. Thus, it is shown the gripper can successfully grasp objects with different shapes and sizes and can used with further customisation for research and educational purposes.

The maximum gripping force at the tip of the robotic gripper prototype has been experimentally estimated as 9 N. However, due to non-backdriveability of the gripper actuating mechanism, the gripper fingers may resist much larger forces that they actually exert [34].

IV. GRIPPER PLATFORM MODIFICATION

The simple design of the proposed open-source 3D-printed gripper platform can be easily customized for research and educational purposes. For instance, to provide an adaptive passive object grasping an underactuated three finger robotic gripper should actuate fingers independently from each other. In general, the underactuation principle between the fingers can be achieved using differential mechanisms. Various differential actuation mechanisms between fingers, such as gear differentials, linkage seesaw differentials, and pulley differentials can be applied [19], [35]. Gear differential mechanisms result to relatively high space requirements whereas linkage seesaw and pulley differential systems have payload capacity limitations. Previously, a novel breakaway clutch mechanism was presented in [36] to accomplish enveloping grasping of a three finger end effector. Underactuation between the fingers can also be provided by an one-input/three-output differential as proposed in [37].
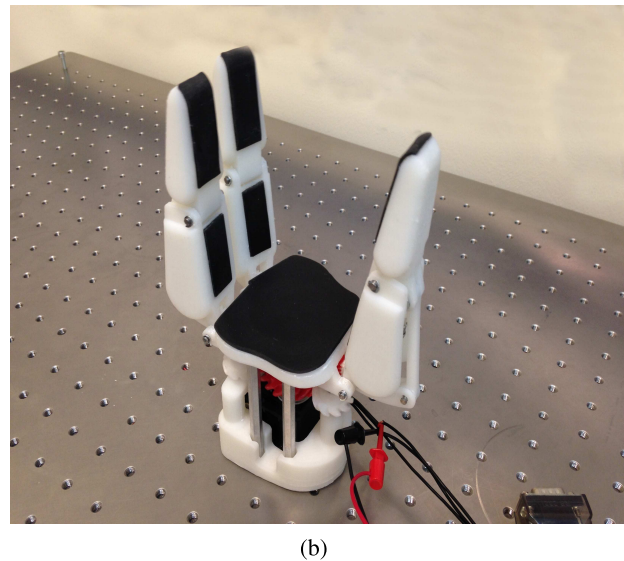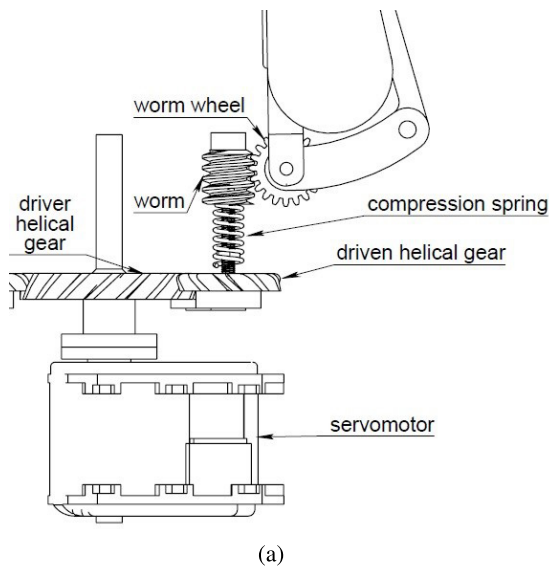
FIGURE 9. 2D model of breakaway clutch mechanism (a) and a 3D-printed adaptive gripper prototype (b).

A. ADAPTIVE GRIPPER WITH A BREAKAWAY CLUTCH MECHANISM

To demonstrate easiness of modification and add adaptivity to the open-source gripper platform the authors have proposed a modified gripper platform with a breakaway clutch mechanism that provides underactuation between fingers. The detailed presentation of the breakaway clutch mechanism is outlined in [38]. The architecture of the breakaway clutch mechanism for a single finger consists of two helical gears, a worm wheel, a worm and a compression spring and is shown in Fig. 9. As all the three fingers of the adaptive gripper are driven by a single actuator, the actuation is transmitted from the actuator to the fingers through a series of gears. To achieve the full wrapping of an object, the underactuation principle is used between the individual fingers for providing maximum grasp contact. If a finger is blocked by contacting with an object, other fingers still move to complete their closing sequence. This is achieved due to presence of the driven helical gear that is able to slide along its vertical axis while rotating, thus disconnecting the blocked finger from the driving helical gear wheel. Note that the modified gripper platform now contains two springs that should be accurately chosen in order to activate proper underactuation.

All three fingers of the robotic gripper are pivoted to the palm in a way that allows executing the grasping configurations without changing orientations of the finger bases. The main grasping patterns of the modified robotic gripper can be summarized to three main configurations: cylindrical, spherical and planar [39], as illustrated in Fig. 10. Fig. 11 illustrates the performance of the 3D-printed modified gripper prototype while grasping a number of objects with different shapes. It can be seen that the gripper fingers are able to adapt to the shapes of the grasped objects. For instance,
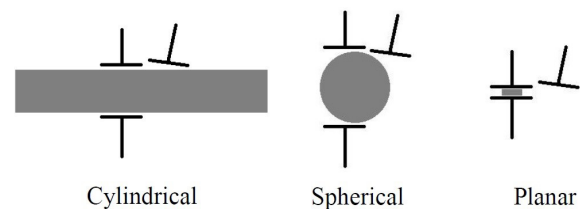

FIGURE 10. Main grasping configurations with the finger layout of the adaptive robotic gripper.

the cylindrical grasping pattern is achieved by holding an object with two fingers situated opposite to each other, whereas the third finger ensures the grasp stability. This prevents unstable grasps and allows gripping cylindrical objects without prior knowledge of their center of mass. During spherical grasping fingers adapt to the shape of the object and fully envelope it. Planar grasping is performed at tip phalanxes using all three fingers, while fingertip grasp uses only two fingers for picking up small objects, which is not available in the original gripper platform. The video of the adaptive gripper performance is available at (www.alaris.kz).

B. DIFFERENTIAL GEAR MECHANISM

As an alternative option, the gripper platform may be modified to accommodate differential mechanisms. Similar to [37], the authors suggest to employ one input/two output differential gear mechanisms that can actuate two fingers independently. All three gripper fingers can be actuated through series connection of two differential gears. A conventional spur gear differential is formed from two equivalent coaxial epicyclic gear trains assembled with a gear cage such that their planet gears are engaged. The authors have designed an example of the modified one input/two output differential gear mechanism that also uses the cage as a carrier (i.e. input) as illustrated in Fig. 12.
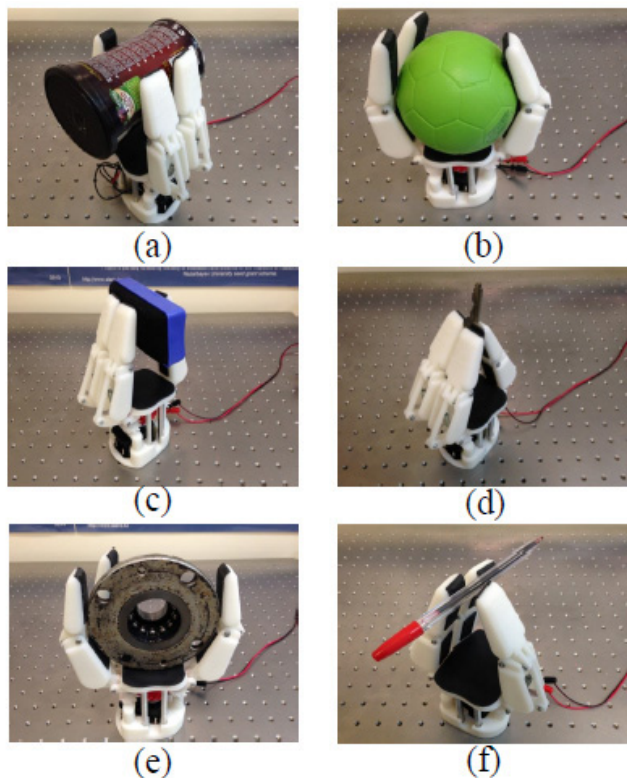
FIGURE 11. Grasping of different objects by the 3D-printed adaptive gripper prototype: (a) Cylindrical grasp. (b) Spherical grasp. (c) Planar grasp. (d) Fingertip grasp. (e) High payload, large shape grasp. (f) Low payload, small shape grasp.
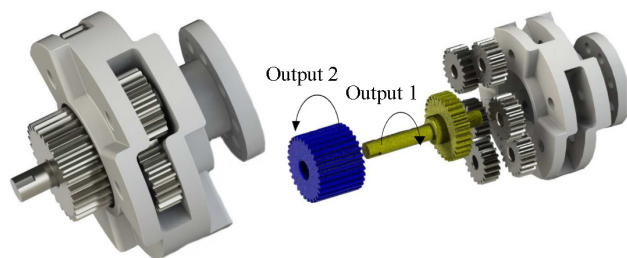

FIGURE 12. Rendered isometric and exploded views of the proposed differential gear mechanism.

The mechanism coaxial outputs are located on one side of the cage. The motion is applied to the gear cage which works as a carrier, i.e. the gear input. This design employs simple mechanical parts, which can be easily manufactured in a machine shop or 3D-printed and be embedded into the gripper platform without large efforts. The CAD model of the presented differential gear is available on request from the paper authors.

V. CONCLUSION

This paper presents the design of an open-source 3D-printed underactuated robotic gripper platform for research and educational purposes. The use of the 3D printing technology to manufacture the gripper prototype ensures its low cost

of production comparing to similar commercially available robotic end effectors. The gripper design model and its experimental prototype are introduced and discussed in detail. In addition, possible modifications of the gripper platform, i.e. an underactuated adaptive gripper with breakaway clutch mechanism and a differential gear mechanism, are briefly presented. It is shown that the the presented robotic gripper with one actuator meets the design objectives in terms of: a) a simple mechanical structure of the gripper due to usage of a four-bar linkage mechanical system for finger design and a single actuation; b) a low cost due to utilizing of a single off-the-shelf actuator and 3D printing technologies; c) relatively high payload comparable with similar size tendon driven robotic end effectors.

The 3D model of the gripper is created using the SolidWorks CAD software and is available for downloading from the authors' research lab website (www.alaris.kz). Similar to [19], the open-source gripper platform aims to overcome constraint of the rigid, closed designs of existing robotic end effectors. The simple three finger robotic gripper CAD model released open-source for public use would allow researchers modifying the design for both the research and educational purposes. For instance, to facilitate research on autonomous grasping of different shape objects, sensing elements such as tactile sensors for force feedback capabilities and a depth camera for object recognition can be embedded into the gripper platform.

REFERENCES

[1] E. Canessa, C. Fonda, and M. Zennaro, Eds., *Low-cost 3D Printing for Science, Education & Sustainable Development*. Trieste, Italy: ICTP, 2013.

[2] G. C. Anzalone, C. Zhang, B. Wijnen, P. G. Sanders, and J. M. Pearce, "A low-cost open-source metal 3-D printer," *IEEE Access*, vol. 1, pp. 803–810, 2013.

[3] C. Zhang, N. C. Anzalone, R. P. Faria, and J. M. Pearce, "Open-source 3D-printable optics equipment," *PLoS ONE*, vol. 8, no. 3, p. e59840, 2013.

[4] J. M. Pearce, "Building research equipment with free, open-source hardware," *Science*, vol. 337, no. 6100, pp. 1303–1304, 2012.

[5] G. Carbone, Ed., *Grasping in Robotics* (Mechanisms and Machine Science). New York, NY, USA: Springer-Verlag, 2012.

[6] C. Liu, H. Qiao, J. Su, and P. Zhang, "Vision-based 3-D grasping of 3-D objects with a simple 2-D gripper," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 44, no. 5, pp. 605–620, May 2014.

[7] J. M. Romano, K. Hsiao, G. Niemeyer, S. Chitta, and K. J. Kuchenbecker, "Human-inspired robotic grasp control with tactile sensing," *IEEE Trans. Robot.*, vol. 27, no. 6, pp. 1067–1079, Dec. 2011.

[8] N. Karnati, B. A. Kent, and E. D. Engeberg, "Bioinspired sinusoidal finger joint synergies for a dexterous robotic hand to screw and unscrew objects with different diameters," *IEEE/ASME Trans. Mechatronics*, vol. 18, no. 2, pp. 612–623, Apr. 2013.

[9] A. Kochan, "Shadow delivers first hand," *Ind. Robot, Int. J.*, vol. 32, no. 1, pp. 15–16, 2005.

[10] S. C. Jacobsen, E. K. Iversen, D. Knutti, R. Johnson, and K. Biggers, "Design of the Utah/M.I.T. dextrous hand," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, vol. 3. Apr. 1986, pp. 1520–1532.

[11] M. Baril, T. Laliberté, C. Gosselin, and F. Routhier, "On the design of a mechanically programmable underactuated anthropomorphic prosthetic gripper," *ASME J. Mech. Design*, vol. 135, no. 12, p. 121008, 2013.

[12] Z. Kappassov, Y. Khassanov, A. Saudabayev, A. Shintemirov, and H. A. Varol, "Semi-anthropomorphic 3D printed multigrasp hand for industrial and service robots," in *Proc. IEEE Int. Conf. Mechatronics Autom.*, Aug. 2013, pp. 1697–1702.

[13] T. Laliberté, L. Birglen, and C. Gosselin, ''Underactuation in robotic grasping hands,'' *Mach. Intell. Robot. Control*, vol. 4, no. 3, pp. 1–11, 2002.

[14] *Schunk 3-Finger Concentric Gripper SGW*. [Online]. Available: http://www.schunk.com/schunk_files/attachments/SGW_gesamt_EN.pdf, accessed May 2015.

[15] *Lacquey Spherical Gripper*. [Online]. Available: http://lacquey.nl/csites/ default/ files/ sheets/ SpecificationSheetSphericalGripper .pdf, accessed May 2015.

[16] *Three-Finger Adaptive Robot Gripper*. [Online]. Available: http://robotiq.com/wp-content/uploads/2014/08/Robotiq-3-Finger-Adaptive-Gripper-Specifications1.pdf, accessed May 2015.

[17] A. Namiki, Y. Imai, M. Ishikawa, and M. Kaneko, ''Development of a high-speed multifingered hand system and its application to catching,'' in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, vol. 3. Oct. 2003, pp. 2666–2671.

[18] *Servo-Electric 3-Finger Gripping Hand SDH*. [Online]. Available: http://www.schunk.com/schunk_files/attachments/SDH_DE_EN.pdf, accessed May 2015.

[19] R. R. Ma, L. U. Odhner, and A. M. Dollar, ''A modular, open–source 3D printed underactuated hand,'' in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2013, pp. 2737–2743.

[20] C.-H. Chen, ''Mechatronics design of multi-finger robot hand,'' in *Proc. 12th Int. Conf. Control, Autom. Syst.*, Oct. 2012, pp. 1491–1496.

[21] R. R. Ma and A. M. Dollar, ''Linkage-based analysis and optimization of an underactuated planar manipulator for in-hand manipulation,'' *J. Mech. Robot.*, vol. 6, no. 1, pp. 011002-1–011002-9, 2014.

[22] Y. Tlegenov, K. Telegenov, and A. Shintemirov, ''An open-source 3D printed underactuated robotic gripper,'' in *Proc. IEEE/ASME 10th Int. Conf. Mechatronic Embedded Syst. Appl. (MESA)*, Sep. 2014, pp. 1–6.

[23] L. Birglen and C. M. Gosselin, ''Geometric design of three-phalanx under-actuated fingers,'' *J. Mech. Design*, vol. 128, no. 2, pp. 356–364, 2005.

[24] T. Laliberté and C. M. Gosselin, ''Underactuated mechanical finger with return actuation,'' U.S. Patent 5 762 390, Jun. 9, 1998.

[25] W. T. Townsend, ''The Barrett Hand grasper-programmably flexible part handling and assembly,'' *Ind. Robot, Int. J.*, vol. 10, no. 3, pp. 181–188, 2000.

[26] Kinova. *JACO Research Edition*. [Online]. Available: http://kinovarobotics.com/wp-content/uploads/2013/05/kinova-jaco-spec-sheet.pdf

[27] S. Montambault and C. M. Gosselin, ''Analysis of underactuated mechanical grippers,'' *J. Mech. Design*, vol. 123, no. 3, pp. 367–374, 2001.

[28] L. Birglen and C. M. Gosselin, ''Kinetostatic analysis of underactuated fingers,'' *IEEE Trans. Robot. Autom.*, vol. 20, no. 2, pp. 211–221, Apr. 2004.

[29] I. A. Bonev, D. Zlatanov, and C. M. Gosselin, ''Singularity analysis of 3-DOF planar parallel mechanisms via screw theory,'' *J. Mech. Design*, vol. 125, no. 3, pp. 573–581, 2003.

[30] *UP Plus 3D Printer*. [Online]. Available: http://www.pp3dp.com/, accessed May 2015.

[31] *Stratasys ABS Material Properties*. [Online]. Available: http://www.nrri.umn.edu/NLTC/ABS07.pdf, accessed May 2015.

[32] *Dynamixel MX-28*. [Online]. Available: http://support.robotis.com/en/product/dynamixel/mx_series/mx-28.htm, accessed May 2015.

[33] *The Robot Operating System (ROS)*. [Online]. Available: http://www.ros.org/, accessed May 2015.

[34] S. J. Bartholet, ''Reconfigurable end effector,'' U.S. Patent 5 108 140, Apr. 28, 1992.

[35] L. Birglen and C. M. Gosselin, ''Force analysis of connected differential mechanisms: Application to grasping,'' *Int. J. Robot. Res.*, vol. 25, no. 10, pp. 1033–1046, 2006.

[36] N. T. Ulrich, ''Methods and apparatus for mechanically intelligent grasping,'' U.S. Patent 4 957 320, Mar. 26, 1996. [Online]. Available: https://www.google.kz/patents/US4957320

[37] T. Laliberté and C. Gosselin, ''Actuation system for highly underactuated gripping mechanism,'' U.S. Patent 6 505 870, Jan. 14, 2003. [Online]. Available: https://www.google.kz/patents/US6505870

[38] K. Telegenov, Y. Tlegenov, and A. Shintemirov, ''An underactuated adaptive 3D printed robotic gripper,'' in *Proc. 10th France–Jpn./8th Eur.–Asia Congr. Mecatronics (MECATRONICS)*, Nov. 2014, pp. 110–115.

[39] T. Laliberté and C. M. Gosselin, ''Underactuation in space robotic hands,'' in *Proc. 6th Int. Symp. Artif. Intell. Robot. Autom. Space (i-SAIRAS)*, 2001, pp. 1–8.

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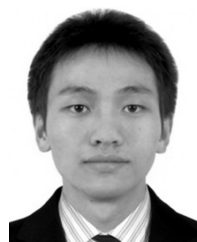
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