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An Open-Source Reconfigurable Robotic Gripper with Detachable Fingers

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***Abstract*—This paper presents a new open-source 3-fingered robotic gripper with a reconfigurable modular structure for extending the choice of reconfigurable robotic gripper designs freely available to robotics research community. Combination of unique design solutions, such as independent and modular (detachable) finger modules, which provide finger position and orientation reconfigurability and adaptivity to different shape objects, is experimentally demonstrated in a functional 3D-printed robotic gripper prototype. The proposed gripper prototype was built using off-the-shelf inexpensive components and 3D printing technology, ensuring low manufacturing cost and replicability. The paper also outlines the gripper control and demonstrates its performance in grasping different shape objects. The open-source design of the presented robotic gripper will be freely available for downloading from the authors' research lab website https://www.alaris.kz and https://github.com/alarisnu/alaris_LCRDF_Gripper upon further modernization, outlined in the future work discussion.**

***Index Terms*—robotic gripper, robotic end-effector, reconfigurable kinematics, reconfigurable gripper, adaptive gripper, mechatronic design.**

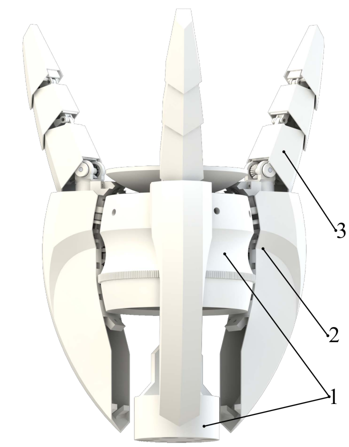

Fig. 1. Proposed open-source reconfigurable gripper concept: 1 - gripper base, 2 - finger base with cover, 3 - linkage-based three-phalange finger with phalange covers.

I. Introduction

Widespread deployment of industrial and service robots in industrial and domestic applications lead to increased development of novel robotic grippers. A large variety of multi-fingered robotic gripper designs were proposed over the past decades, which can be generally divided into different categories: classical grippers, made of rigid links interconnected in various joints, e.g. [1]–[4], soft grippers, that utilize tendons in combination with elastic materials [5] or are made of specific materials implementing octopus-like behavior in which hydraulic or pneumatic actuators are used to transform one shape into another, e.g. [6], [7] and their design combinations, e.g. [8]–[10]. Another design based on two different types of passive gear trains; one was stiff and the other was elastic, can be seen in [11]. Further, grippers can be divided into adaptive and reconfigurable. Here, reconfigurability is referred to the ability to change the orientation and position of each robotic finger relative to the gripper base. It should be fully actuated, i.e. each finger position and orientation should be controlled independently [12], [13]. On the other hand, adaptive grippers can adapt to various shapes due to the use of underactuated or soft finger designs [2], [14], [15].

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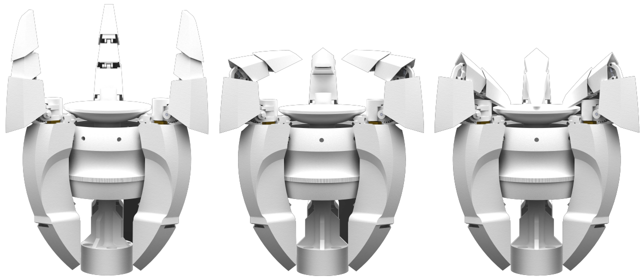
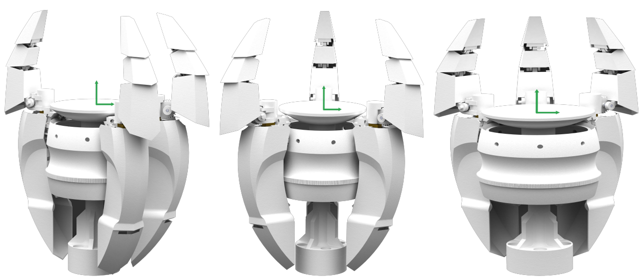
Conducted analysis of available reconfigurable gripper developments revealed that there is still exist a demand for novel robotic gripper designs. This can be attributed to the presence of numerous proposed designs of adaptive anthropomorphic hands, suction end-effectors and highly compliant soft grippers with fingers fixed on the end-effector palms, that may restrict applicability of such end-effectors to grasping limited shape objects. Moreover, commercially available robotic grippers are not always affordable due to high cost, and in most of cases they do not allow design customisation for integration of additional sensors for research purposes and specific applications [5]. To address such problems 3D printing rapid prototyping technology is actively applied for manufacturing of low-cost robotic end-effectors that can be used in research and education [16]. This is facilitated through public release of open-source computer-aided design (CAD) models of robotic end-effectors that can be easily prototyped and using low-cost 3D printers and off-the-shelf components, e.g. [2], [5], [17]–[19].

In this paper, we propose a novel design of a low-cost robotic gripper with reconfigurable kinematic structure (Fig. 1). The presented gripper design has three modular (detachable) fingers moving around a circular gripper base (position) and their vertical axes (orientation) a shown in Figs. 2 and 3. The realized



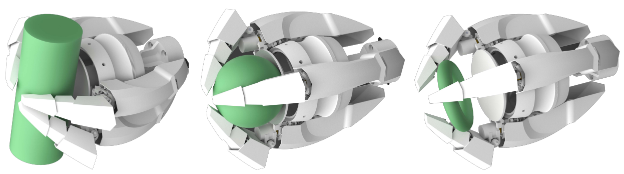
(a) (b) (c)

Fig. 2. Grasping motions: (a) open position, (b) middle-closed position and (c) closed position.



(a) (b) (c)

Fig. 3. Turning motions: (a) 2 fingers opposite 1 finger, (b) the same distance between fingers, (c) fingers in line.

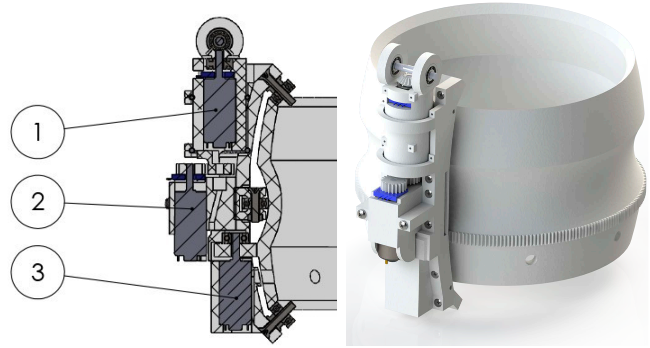


(a) (b) (c)

Fig. 4. Object grasping examples.

capability of the finger modules to independently modify their position and orientation coupled with adaptive finger kinematics provides high grasping performance of various shape objects as demonstrated in Fig. 4. The proposed open-source mechanical design of the robotic hand has been created using SolidWorks CAD software and is freely available for downloading from the authors' research lab web-site https://www.alaris.kz and https://github.com/alarisnu/alaris_LCRDF_Gripper, so it can serve as a low-cost design platform for further customization for research and educational purposes.

The paper is organized as follows. Section II presents the robotic gripper concept and the gripper base design, while Section III outlines the gripper finger design. The experiential proof-of-concept prototype of the gripper is then presented in Section IV, while its object grasping performance is experientially evaluated in Section V. Conclusion and Future Work section summarizes main contributions of the paper and outlines future improvements of the proposed gripper design.



(a) (b)

Fig. 5. (a) Cross-sectional view of the finger base design with actuators, (b) Rendered 3D view of the gripper base assembled with a finger base.

II. Robotic Gripper Design

The primary design requirements were emphasised for designing a reconfigurable robotic gripper aiming to realize gripper adaptation to various shape objects: a) the finger modules should be completely movable around the gripper base; b) the finger itself should be able to rotate around its own Z axis, i.e. the finger closing-opening and yaw rotation are realized.

As a result of a preliminary literature review, e.g. [20], a monorail train with a wheel system was chosen for providing both smooth motion and proper fixation of the finger modules along/to the base rails. In this way, the movable finger modules act as "trains" sliding along the circular "rails" on the gripper base. Both suspended and straddled monorails require wheel axes enveloping the rails from several sides. There are various approaches to arranging the wheels. While part of them is needed to deal with the weight of the train (load wheels), others squeeze the rail from sides (guide wheels).

The proposed design of the gripper base with finger transmission system in 3D and cross section views are shown in Figs. 5(b) - 5(a). The rail profile has three contact faces for the wheels. While upper and lower wheels axes are 45 degrees to the horizontal plane and symmetric to each other, the central wheel axis is vertical. Wheel axes form an isosceles triangle. Left side central wheel and right side pair of upper and bottom wheels squeeze the rails. This mounting resembles jaw grippers and is based on monorail train wheels holding the rails from three sides. A more than 90 degree angle between the wheel axes is arranged for better gripper mobility.

The actuator positions in a finger base is detailed in Fig. 5(a). The finger closing - opening operation depicted in Fig. 2 is done by the upper actuator (1). The actuator torque is transmitted to the finger via straight miter gears pair. Actuator (2) rotates the inner finger module encapsulating Actuator 1 and the finger mount as seen in Fig. 5(b). Actuator (3) drives the whole finger module along the circular guides on a gripper base through spur gear transmission as shown in Fig. 3.

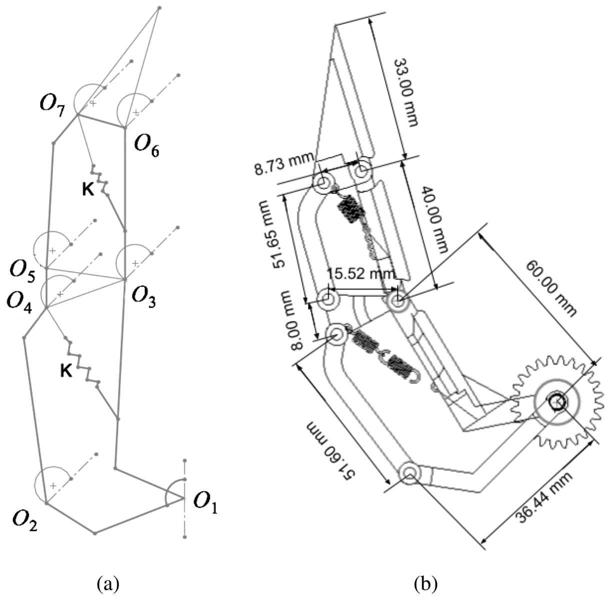


Fig. 6. (a) Gripper finger kinematics; (b) Finger linkage system design with dimensions.

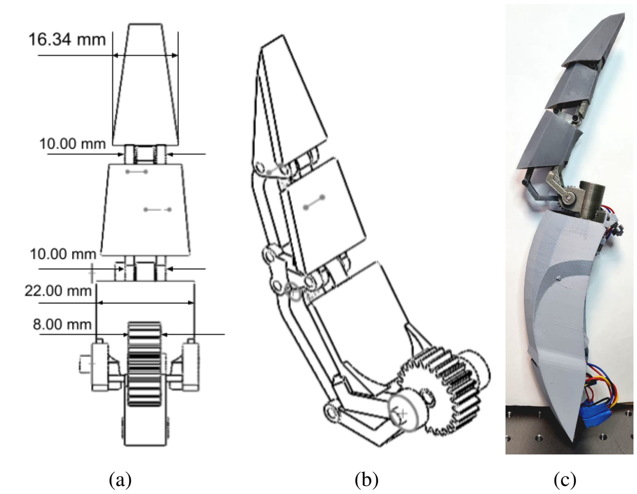


Fig. 7. (a) Finger width dimensions; (b) 3D CAD finger model ; (c) Assembled experimental prototype of a gripper finger module.

III. Finger Design and Kinematics

A. Finger Design

For design simplicity the presented robotic gripper utilizes three identical finger modules with each finger designed as an adaptation of an underactuated adaptive finger design presented in [2], [21]. The design utilizes a planar 4-bar mechanical linkage-based system, which is the one of the main design objectives for the proposed open-source gripper. Figure 6(a) demonstrates the finger kinematic configuration. Each rotation point is identified with a letter and a subscript. The finger phalanges are linked with springs (K is stiffness). In overall, the finger kinematics combines a sequence of two 4-bar linkage mechanisms with the lower one being the actuating linkage with a bevel gear for power torque transmission from the finger actuator located in the finger base through a worm gear transmission. Thus, the gripper fingers are designed to be non-back drivable, that allows to hold objects with by a closed gripper with the finger actuators powered off.

The finger linkage geometry in Fig. 6(b) was optimized using the SolidWorks' Sketch Blocks, the widely used tool for in planar mechanism design based on iterative testing of simplified actuated 3D printed finger models for achieving desired finger workspace. Fig. 7(a) demonstrates the finger width dimensions, whereas Fig. 7(b) and Fig. 7(c) shows the sketch designed in SolidWorks and a physical prototype of the finger.

B. Kinematics analysis

The stiffness of the finger passive element, i.e. the spring coefficient *K*, which in turn provides actuation of the finger's second phalange, can be calculated using the theoretical analysis based on quasi-static equilibrium modelling of a two-phalange underactuated finger and presented in detail in [2], resulting to the following expression:

$$t^T \omega_a = f^T v, \tag{1}$$

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 [22].

Following the calculations in [2], the spring stiffness can be expressed as

$$K = \frac{T_a \dot{\theta_{a_1}} - \zeta_1 \circ \xi_1 - \zeta_2 \circ \xi_2}{\triangle \theta_2 \dot{\theta_2}}, \tag{2}$$

where T_a is the actuation wrench, *K* is the stiffness of the spring, $\dot{\theta_i}$ is first derivative of the phalange joint coordinates, $\zeta_i \circ$ is a shorthand for row vector.

Equation (2) defines the stiffness of the spring that provides the second degree-of-freedom (DOF) for the tip of the finger mechanism, and is used to choose a suitable spring for an individual gripper design. However, in practice an appropriate spring for the finger mechanism can be selected using a trial-and-error approach.

IV. Gripper Prototype and Control Architecture

A. Gripper Prototype

A proof-of-concept experiential prototype of the proposed reconfigurable robotic gripper was manufactured using a 3D printing technology with polylactide (PLA) material. 3D printed parts of the gripper are connected to each other by off-the-shelf 1 mm and 2.5 mm bolts and nuts, embedded to the special niches. The longer bolts are also used as finger and thumb joint shafts. The assembled finger linkages and base mechanisms are closed by specially designed cover elements.

The gripper prototype is rigidly mounted in a vertical position on a circular shape base holder to a laboratory optical plate. The holder can be easily replaced or redesigned for gripper mounting on a robot-manipulator in future. At present stage, power supply and control of the gripper DC actuators is realized

TABLE I
BILL OF MATERIALS.

Name	**Description**	**Quantity**	**Price per piece ($)**	**Sum ($)**
Bearing	623ZZ (3x10x4mm)	11	0.5	5.5
Photocell	GL5528	1	0.2	0.2
Potentiometer	SV01A103AEA01B00	2	5.1	10.2
Motor	JGA12-N20-100	3	6.8	20.4
Arduino UNO	Microcontroller	1	31	31
Arduino MEGA	Microcontroller	1	52.3	52.3
Fasteners	nuts, bolts	50	0.1	5
LEDs	5 mm LED - Green	8	0.06	0.48
Resistors	1k, 10k	13	0.05	0.65
Wires	Pack of wires	3	1.6	4.8
Motor Controller	L293D	2	0.6	1.2
PLA	PLA filament	2	19	38
Overall				169.73

externally from a control PC through an Arduino UNO board (the Main board) with AVR ATMega328 microcontroller that has both UART and I2C peripherals.

The main board checks all messages arrived from a control PC for their destination addresses and forward them over I2C to the gripper fingers. At the same time, each finger module houses, in addition to actuator, sensor and gear elements, a customly designed PCB board with a mounted receiving AtMega328 microcontroller with I2C interface and two L293D dual channel motor drivers for controlling the three DC gearmotor actuators. The finger angular position feedback is supplied to the microcontroller from a mounted potentiometer sensor for controlling the top actuator responsible for finger opening-closing. At this stage a simple proportional controller is realized with a big enough tolerance to ignore sensor noise.

Table I outlines the bill of materials and estimated cost of an experimental prototype of the presented reconfigurable robotic gripper. Actuators, screws and nuts and standoff are available for purchase at various robotics hobby/electronic and mechanical component distributors' web-sites. The overall cost of manufacturing the gripper prototype without its embedded systems is estimated to be around 170 USD. Also, an additional finger module will cost about 72 USD.

B. *Finger Module Position Control*

Figure 8 presents a schematic diagram of the gripper control architecture with connections of the system's electromechanical components. A finger module position on a circular guide of the gripper base is sensed by a light sensor, embedded on the inner side of the finger base. The light sensor detects a light-up LED among 8 LEDs, equally mounted along the circular guide on the gripper base. Whenever a finger module receives a new position command it compares the new and the current position to determine the rotation direction to follow. Then the finger module slides along the gripper base until it reaches a first light-up LED. The LED command is send before the finger move command to prevent the finger overshoot due to unexpected delay between action and communication.

A graphical user interface (GUI) was also designed to provide a convenient way to a user for gripper control as presented in Fig. 9. The GUI shows 8 discrete available positions of the gripper finger modules, corresponding to the positions of 8 LEDs, embedded in equal distance in the gripper base.

V. EXPERIMENTAL RESULTS

Experimental evaluation of the proposed gripper started with time analysis of the finger opening-closing and yaw rotation operations. Figure 10 shows the sensor values from a gripper finger when it freely switches between its open and closed states.

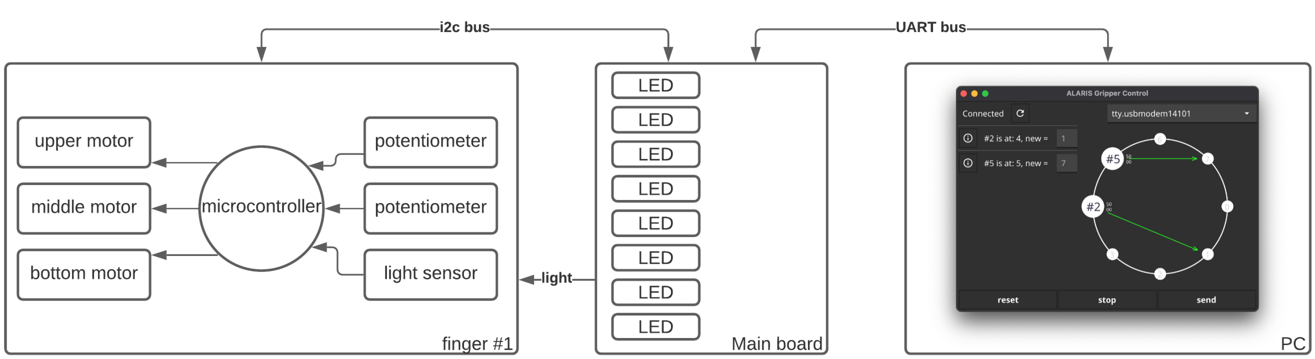
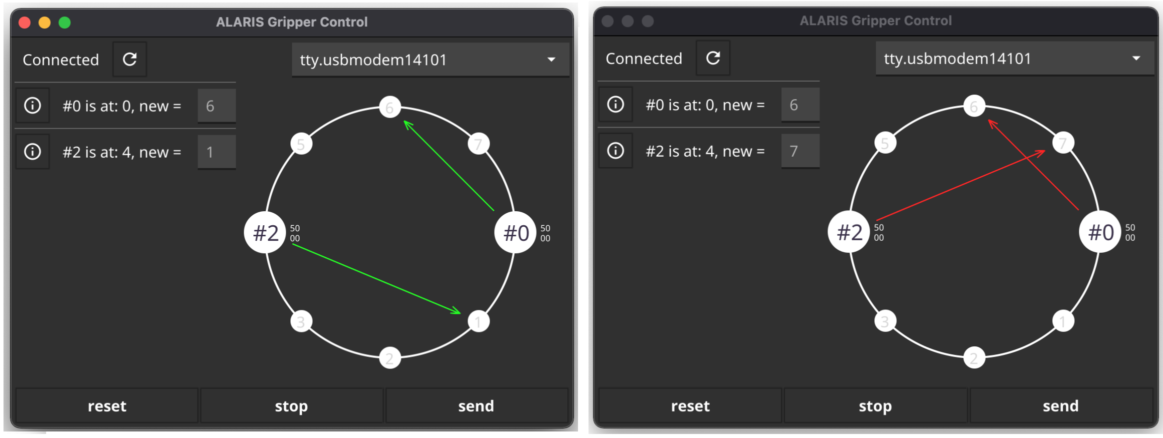


Fig. 8. Gripper Entity Relationship Diagram.



(a)

(b)

Fig. 9. A gripper control GUI with demonstration of valid (a) and invalid (b) fingers trajectories.

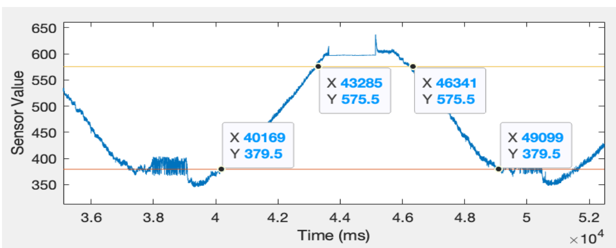


Fig. 10. Opening and closing of a gripper finger.

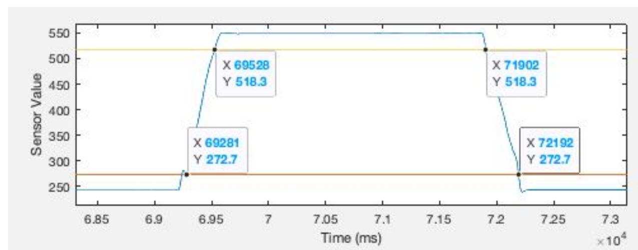


Fig. 11. Rotation of a gripper finger.

The oscillation on the plot occurs when the finger touches the base of the gripper due to motor trying to keep up. The dip right after oscillations is a backlash of gears. Then the plot steadily goes up as finger approaches open state. It takes 3 full seconds to rise from 10% to 90% and another 3 seconds to close back.

Figure 11 shows rotation trajectory of the gripper finger. The finger has different set of gears for rotation and closing, that is why it only takes about 247 ms for a finger to rotate from left to right and another 290 ms to reach previous position.

The effective grasping of objects with different shapes and sizes is one of the important gripper design requirements. Figure 12 illustrates the performance of the gripper in grasping a number of objects with different shapes. As seen from the figure, while grasping a cylindrical object, e.g. a bottle, the grasping pattern is achieved by holding the object with two fingers situated opposite to the third one. On the other hand, a spherical object, e.g. a ball, is securely grasped by symmetrically located finger modules with fingers facing the gripper center point. At the same time, while grasping complex shape objects with strong asymmetric geometry, all the three gripper fingers wrap of the object with different degree of bending depending on the object shape. For example, in the case of grasping of a mobile phone object, one finger moves as a single rigid body while the others actuate the second finger DOF and envelop the object. After performing numerous experimental trials and observations it was confirmed that the proposed 3D-printed reconfigurable gripper prototype provides successful grasping of objects with different shapes and sizes in various finger module positions, thus demonstrating the gripper reconfigurability.

The video demonstration of the presented reconfigurable gripper is available in the supplementary media, accompanying this publication, and at the author's research lab web-site https://www.alaris.kz.

VI. Conclusion and Future Work

In this paper, a new open-source design of a 3-fingered reconfigurable robotic gripper is presented to extend the choice of robotic gripper designs freely available to robotics researchers. Combination of presented and discussed in the paper unique design solutions such as independent and modular (detachable) finger modules, providing finger positions and orientation reconfigurability and adaptivity to different shape objects, is experimentally demonstrated in a functional 3D-printed robotic gripper prototype. The proposed gripper prototype was built using off-the-shelf inexpensive components and 3D printing technology ensuring low manufacturing cost and replicability. The robotic gripper was experimentally tested with a variety of objects in grasping tasks and operation time measurements, which demonstrated the feasibility for its utilization in robotic research applications.

Future work will focus on further gripper design improvement through eliminating the present limitations of the

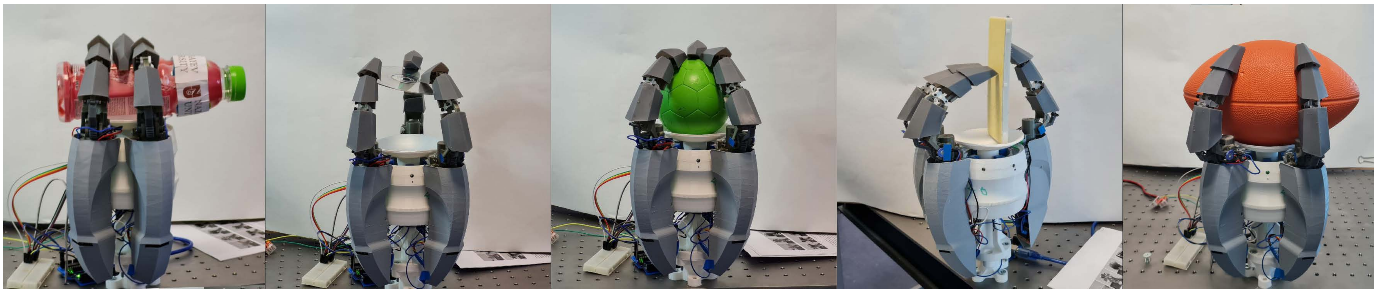


Fig. 12. Grasping of different shape objects by the 3D-printed reconfigurable gripper prototype (left-to-right): cylindrical grasp, planar grasp, spherical grasp, fingertip grasp, high payload, large shape grasp.

gripper, such as slow finger movements, etc. This could include equipping the gripper with embedded sensing elements such as tactile sensors for force feedback capabilities for fragile/deformable object grasping functionality. In addtion, a depth camera sensor can be embedded for implementation of autonomous gripper finger reconfigurability depending on object type/shape. Eventually, the gripper prototype should be mounted on an industrial manipulator for evaluating its grasping performance in real-life scenarios.

Upon realization of several further modifications the presented open-source mechatronic design of the robotic gripper will be freely available for downloading from the authors' research lab https://www.alaris.kz and https://github.com/alarisnu/alaris_LCRDF_Gripper, aiming to serve as a low-cost design platform for further customization and utilization in research and industrial applications.

References

[1] S. B. Backus and A. M. Dollar, "An adaptive three-fingered prismatic gripper with passive rotational joints," *IEEE Robotics and Automation Letters*, 2016.

[2] K. Telegenov, Y. Tlegenov, and A. Shintemirov, "A low-cost open-source 3-D-printed three-finger gripper platform for research and educational purposes," *IEEE Access*, vol. 3, pp. 638–647, 2015.

[3] F. Chen, F. Cannella, C. Canali, A. Eytan, A. Bottero, and D. Caldwell, "Theoretical and kinematic solution of high reconfigurable grasping for industrial manufacturing," *IEEE International Conference on Robotics and Biomimetics (ROBIO)*, 2013.

[4] C. I. Basson, G. Bright, and A. J. Walker, "Analysis of flexible end-effector for geometric conformity in reconfigurable assembly systems: Testing geometric structure of grasping mechanism for object adaptibility," *Pattern Recognition Association of South Africa and Robotics and Mechatronics*, 2017.

[5] R. Ma, L. Odhner, and A. Dollar, "A modular, open-source 3D printed underactuated hand," in *Proceedings of the 2013 IEEE International Conference on Robotics and Automation (ICRA)*, 2013, pp. 2737–2743.

[6] V. Ho and S. Hirai, "Design and analysis of a soft-fingered hand with contact feedback," *IEEE Robotics and Automation Letters*, vol. 2, no. 4, pp. 1909–1916, 2017.

[7] Y. T. Z. Wang and S. Hirai, "A prestressed soft gripper: Design, modeling, fabrication, and tests for food handling," *IEEE Robotics and Automation Letters*, vol. 2, no. 2, pp. 491–498, 2017.

[8] D. R. M. C. M. T. T. P. Glick, S. A. Suresh and A. Parness, "A soft robotic gripper with gecko-inspired adhesive," *IEEE Robotics and Automation Letters*, vol. 3, no. 2, pp. 903–910, 2018.

[9] I. Hussain, "Modeling and prototyping of an underactuated gripper exploiting joint compliance and modularity," *IEEE Robotics and Automation Letters*, vol. 3, no. 4, pp. 2854–2861, 2018.

[10] S. S. W. Park and J. Bae, "A hybrid gripper with soft material and rigid structures," *IEEE Robotics and Automation Letters*, vol. 4, no. 1, pp. 65–72, 2019.

[11] R. O. H. Hirano, K. Akiyama, *roc. of the 2016 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, Dejeon, Korea*.

[12] G. Li, C. Fu, F. Zhang, and S. Wang, "A reconfigurable three-finger robotic gripper," *IEEE International Conference on Information and Automation*, 2015.

[13] "Sandia Hand," https://www.sandia.gov/research/robotics/advanced_manipulation/Sandia_Hand.html.

[14] C. Li, X. Gu, and H. Ren, "Design, characterization, and implementation of a two-dof fabric-based soft robotic arm," *IEEE/ASME Transactions on Mechatronics*, 2017.

[15] J. S. Dai, D. Wang, and L. Cui, "Orientation and Workspace Analysis of the Multifingered Metamorphic Hand - Metahand," *IEEE Transactions on Robotics*, vol. 25, no. 4, pp. 942–947, 2009.

[16] Z. Kappassov, Y. Khassanov, A. Saudabayev, A. Shintemirov, and H. A. Varol, "Semi-anthropomorphic 3D printed multigrasp hand for industrial and service robots," in *Proceedings of the IEEE International Conference on Mechatronics and Automation (ICMA 2013)*, 2013, pp. 1697–1702.

[17] N. Krausz, R. Rorrer, and R. Weir, "Design and fabrication of a six degree-of-freedom open source hand," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 24, no. 5, pp. 562–572, 2016.

[18] C. Piazza, G. Grioli, M. G. Catalano, and A. Bicchi, "A century of robotic hands," *Annual Review of Control, Robotics, and Autonomous Systems*, vol. 2, 2019.

[19] A. Nurpeissova, T. Tursynbekov, and A. Shintemirov, "An Open-Source Mechanical Design of ALARIS Hand: A 6-DOF Anthropomorphic Robotic Hand," in *Proceedings of the 2021 IEEE International Conference on Robotics and Automation (ICRA 2021)*, 2021.

[20] A. Heravi, D. Ahmad, I. A. Hameed, R. R. Shamshiri, S. K. Balasundram, and M. Yamin, "Development of a field robot platform for mechanical weed control in greenhouse cultivation of cucumber," in *Agricultural Robots*, J. Zhou and B. Zhang, Eds. IntechOpen, 2018, ch. 2. [Online]. Available: https://doi.org/10.5772/intechopen.80935

[21] L. Birglen and C. Gosselin, "Geometric design of three-phalanx underactuated fingers," *ASME Journal of Mechanical Design*, vol. 128, no. 2, pp. 356–364, 2005.

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