The GR2 Gripper: An Underactuated Hand for Open-Loop In-Hand Planar Manipulation

Nicolas Rojas, Raymond R. Ma, and Aaron M. Dollar

***Abstract*—Performing dexterous manipulation of unknown objects with robot grippers without using high-fidelity contact sensors, active/sliding surfaces, or *a priori* workspace exploration is still an open problem in robot manipulation and a necessity for many robotics applications. In this paper we present a two-fingered gripper topology that enables an enhanced predefined in-hand manipulation primitive controlled without knowing the size, shape, or other particulars of the grasped object. The in-hand manipulation behavior, namely, the planar manipulation of the grasped body, is predefined thanks to a simple hybrid low-level control scheme and has an increased range of motion due to the introduction of an elastic pivot joint between the two fingers. Experimental results with a prototype clearly show the advantages and benefits of the proposed concept. Given the generality of the topology and in-hand manipulation principle, researchers and designers working on multiple areas of robotics can benefit from the findings.**

***Index Terms*—Dexterous hands, gripper design, in-hand manipulation, robot grippers.**

I. Introduction

While single-degree-of-freedom (1-DOF) two-finger robot grippers, due to their mechanical simplicity, reliability, low cost, and force capabilities, are prevalent in industrial and research settings, they can be limited outside of pick-and-place operations. The alignment of parts before assembly processes (e.g., a peg-in-hole alignment task) exemplifies the type of limitations of these minimalist grippers. Although general-purpose and redundant robot arms, additional mechanisms like passive wrists with remote-center-of-compliance [1], or motion-planning strategies such as regrasping [2] can be used to perform alignment operations, these solutions present their own significant limitations and challenges. For instance, space constraints in the environment or joint limits in the arm configuration space may not allow for certain motion trajectories or the addition of supplementary mechanisms. This certainly can be worse in unstructured environments, where the obstacles are mostly unknown and functional shortcomings can occur [3].

In order to mitigate these inconveniences, it can be more advantageous, efficient, and general to augment the capabilities of the gripper in such a way that the system can independently adjust for expected misalignments by reorienting the object once it is grasped. This reorientation of the gripped object is an example of in-hand (or within-hand) prehensile manipulation [4]. In this type of dexterous task, the object is moved within the gripper workspace while the fingers maintain a stable grasp on the object. If the grasped object is repositioned and changes the contacts, the manipulation is called in-hand manipulation with motion at contact; otherwise, it is referred to as precision manipulation. In any case, in-hand manipulation operations increase the variety of tasks that a robotic system can complete.

Researchers have extended basic grippers in various ways to enhance their in-hand manipulation capabilities. For instance, Bicchi and Marigo [5] attached actuated turntables to a parallel-finger gripper and Tincanci *et al.* [6] similarly implemented conveyor-belt surfaces in place of finger pads on a gripper with revolute–revolute serial fingers. Both cases could use these active surfaces to reorient the object while independently maintaining a stable grasp. Designed explicitly for use in industrial assembly tasks and known objects, a jaw-like gripper with sliding finger surfaces was introduced by Chen *et al.* [7]. This additional functionality also served to increase the grasp stability and acquisition range. Other similar approaches have also been proposed [8]. Alternatively, underactuation and mechanical intelligence have been leveraged to enable multiple adaptive grasping modes with simple gripping mechanisms [9], [10]. This approach enhances gripper capability with minimal additional overhead in mechanical complexity.

Robot grippers with two fingers can be kinematically classified, according to the pair elements used in their construction, as linkage type, gear-and-rack type, cam-actuated type, screw type, rope-and-pulley type, or some combination [11]. In the case of linkage-based grippers, Belfiore and Pennestri presented an atlas of 64 possible topologies that use 1-DOF linkages of up to six links as fingers [12]. From all these options, one of the most popular gripper topologies used in all type of robotics applications is in which each finger is a four-bar linkage that, in most practical implementations, corresponds to a parallelogram. Fig. 1 shows a generic instance of this traditional two-finger robot gripper, a mechanism that has been historically employed only for fixturing operations.

In recent years, it has been shown that, by using adaptive mechanical systems, two-finger grippers with revolute–revolute serial fingers can be modified to perform repeatable and robust

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This paper has supplementary downloadable material available at http://ieeexplore.ieee.org, provided by the author. The material consists of a video, entitled "GR2_ManipulationExamples.mp4", which presents a prototype of the GR2 gripper in-hand manipulating relevant examples of the test objects described in Section IV. The size of the video is 21.4 MB.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

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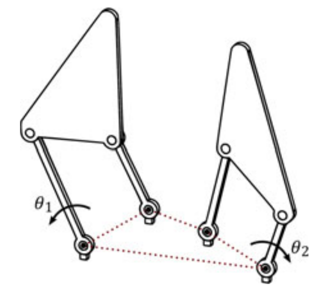

Fig. 1. Traditional two-finger robot gripper with four-bar-linkage fingers. This simple topology is one of the most popular used in all types of robotics applications.

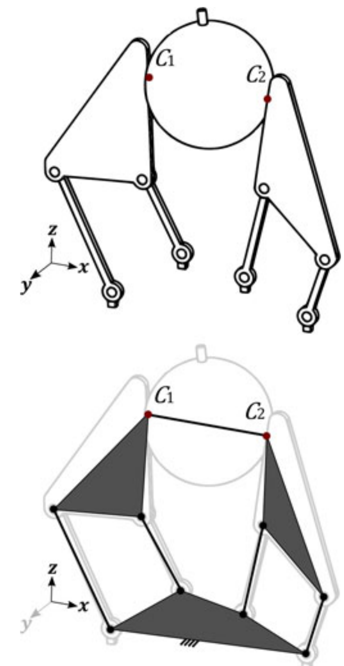

Fig. 2. Hand–object system associated with a traditional two-finger robot gripper when manipulating an object (top) can be kinematically modeled, assuming point contact with friction, as a 1-DOF Innocenti linkage (bottom).

dexterous manipulation operations, such as the flip-and-pinch task, without using contact sensors or active/sliding surfaces [13]. In this paper, we introduce a further twist to this design approach by showing that a simple modification in the topology of the traditional two-finger robot gripper allows an enhanced predefined in-hand manipulation behavior that can be easily controlled without knowing the size or shape of the object *a priori*. Furthermore, this can be implemented open loop, which is without feedback control, while still being robust to the size or shape of the object. We call this concept the grasp–reposition–reorient (GR2) gripper.

The rest of this paper is organized as follows. Section II discusses the theoretical possibilities and limitations of performing in-hand manipulation operations with traditional two-finger grippers. Section III introduces the GR2 gripper concept for the enhanced in-hand manipulation of unknown objects and describes its novel topology, low-level control scheme, and operation. Section IV presents a prototype of the proposed gripper along with results of in-hand manipulation experiments; a video extension that demonstrates its capabilities is also provided. Finally, we conclude in Section V with a summary of the main contributions and prospects for future research.

II. Beyond Grasping With Traditional Two-Finger Robot Grippers

From the viewpoint of its structural characteristics, the arrangement of a gripper based on two four-bar linkages can be classified as a link-fractionated kinematic chain of mobility two, in which the quaternary link associated with the base is denoted as the link of separation (see Fig. 1, dotted lines). Usually, such a fractionated linkage is controlled by a single actuator by coupling the input joints of each finger, say θ_1 and θ_2. In any case, this type of gripper layout has been widely used solely for grasping operations, without considering any feasible capacity for dexterity. Dexterous tasks have been principally related in the literature to multifinger hands with articulated multi-DOF fingers. Although limited by their topology, simple gripping mechanisms can still generate in-hand reorientation and repositioning of the grasped object by properly controlling their input joints.

Fig. 2(top) depicts a traditional two-finger robot gripper grasping an object. The manipulation capabilities of this basic gripping mechanism are analyzed by assuming that the contacts between the object and the distal links reduce to single points, say C_1 and C_2, explicitly, by assuming classical point contacts with friction. It is widely known that the kinematic equivalent of this contact model is a spherical pair [14]. Since the intersection of two spherical displacements generates a rotation about the axis defined by their centers, in our case the contact points C_1 and C_2, results show that this rotation of the grasped object cannot be directly controlled by the gripper actuators. In consequence, according to the notation of Fig. 2(top), we can assume a contact model of point contact with friction of one DOF whose kinematic equivalent is a revolute pair in the direction of the y-axis.

The above analysis allows for structurally modeling the hand–object system of a traditional two-finger robot gripper grasping an object as the eight-link 1-DOF linkage depicted in Fig. 2(bottom). This virtual linkage results from connecting the two four-bar linkages formed by contact points C_1 and C_2 and the links of each finger through a binary link that represents the grasped object.

The introduced eight-link planar linkage corresponds to one of the 16 feasible topologies for eight-link nonfractionated linkages of mobility. This particular topology is in fact one of the more complex of its kind, being one of the four 1-DOF kinematic chains of up to eight links whose configuration space embeds in a 2-D distance space [15]. To facilitate our discussion, we call such an eight-link planar kinematic chain the 1-DOF Innocenti linkage, in honor of C. Innocenti, who initially analytically determined the intersections of the motion generated by two distinct four-bar linkages.

Any point attached to a planar linkage of mobility one generates a planar algebraic curve. In the case of the 1-DOF Innocenti

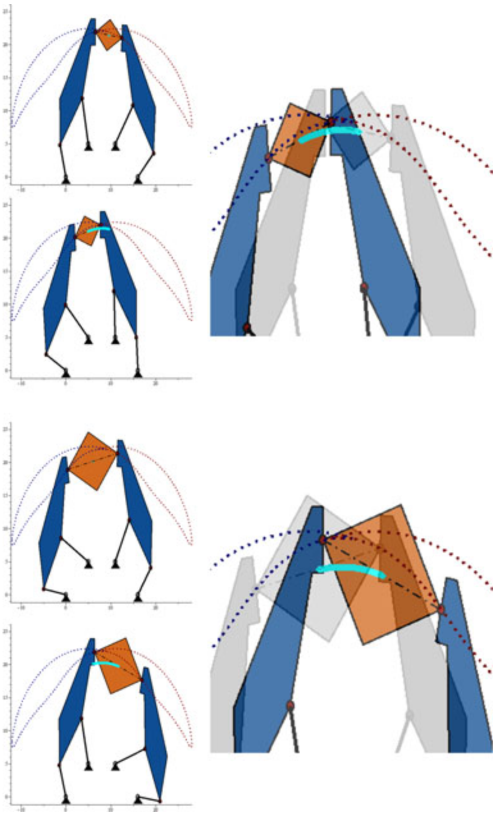

Fig. 3. Simulation of precision manipulations with a traditional two-finger robot gripper based on the structural model of the hand–object system as a 1-DOF Innocenti linkage. The sextic curve of each finger is depicted in the figures and the cyan (light) points correspond to the path traced by the center point of the line segment defined by the contacts. The initial and final configurations are depicted as overlapped in the right side of each inset in grayscale and full color (digital version), respectively.

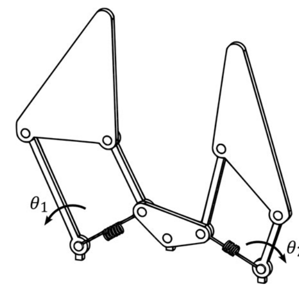

Fig. 4. Generic instance of the GR2 gripper concept for the in-hand manipulation of unknown objects with two-finger robot grippers without using high-fidelity contact sensors or numerical control algorithms. The system, which is based on a novel modification of the topology of the traditional design, preserves the standard grasping operation.

linkage, for the kinematic inversion in which the ground link is the quaternary link, a point attached to the binary link connecting the two four-bar linkages traces a curve that is generally of degree 54. In comparison, a point attached to the output link of a single four-bar linkage traces a curve of degree 6. This analysis implies that an object grasped by the distal links of a traditional two-finger robot gripper may be manipulated following a plane curve that depends on the object's size.

Fig. 3 presents some simulation steps of a traditional two-finger robot gripper performing a precision manipulation of two grasped objects—represented by rhomboid shapes—based on the model of the hand–object system as a 1-DOF Innocenti linkage. The sextic curve of each finger is depicted in the figures and the cyan (light) points trace the path followed by the center point of the line segment defined by the contact points. The initial and final configurations are depicted as overlapped in the right side of each inset in grayscale and full color (digital version), respectively. These simulations can be carried out following, for instance, the procedure for tracing coupler curves of complex pin-jointed linkages described in [15]. These simple examples illustrate the reorientation of grasped objects with traditional two-finger robot grippers, both clockwise and counterclockwise.

Following kinematic structural arguments, the theoretical movements of in-hand manipulation that can be achieved with traditional two-finger robot grippers have been characterized and a 1-DOF Innocenti linkage model of the hand–object system has been proposed. Note that this characterization indeed applies to cases with motion at contact, resulting from rolling or slipping motions, because the system can be modeled as a different 1-DOF Innocenti linkage at each instant. In any case, the feasible range of reorientation of a traditional two-finger robot gripper uniquely depends on the object's size and the location of the contacts, since the dimensions of the base and proximal links cannot be changed. Consequently, any possibility of improving the range of motion of the grasped object comes from the unpredicted reconfigurations in the hand–object system given by changes in the contact points as a result of slippage and rolling.

III. GR2 Gripper Concept for In-Hand Manipulation of Unknown Objects

In this study we introduce the GR2 gripper concept: a two-finger gripper that can perform in-hand manipulation of a varied range of objects without high-fidelity contact sensors or numerical control algorithms. A GR2 gripper is based on a simple modification in the topology of the traditional two-finger robot gripper. This characteristic makes a GR2 gripper a general assembly gripper [16], a gripping mechanism that can be used for traditional pick and place operations as well as for the alignment of parts before assembly tasks. Fig. 4 presents a generic instance of a GR2 gripper; next, we discuss its features.

A. Topology

In a GR2 gripper, shown in Fig. 4, the traditional fixed-geometry base of two-finger robot grippers is transformed into a quaternary link of variable geometry using two ternary links connected through a pivot joint. One of the ternary links corresponds to the grounded base of the gripper. The second ternary link, called the central triangular pivot, rotates around the pivot joint. The remaining revolute joints of the central triangular pivot are connected to the base through tension springs. There are two inputs in the system, say θ_1 and θ_2, one per each finger.

The overall linkage design of a GR2 gripper is similar to some gripping mechanisms that have been proposed [17] and are com-

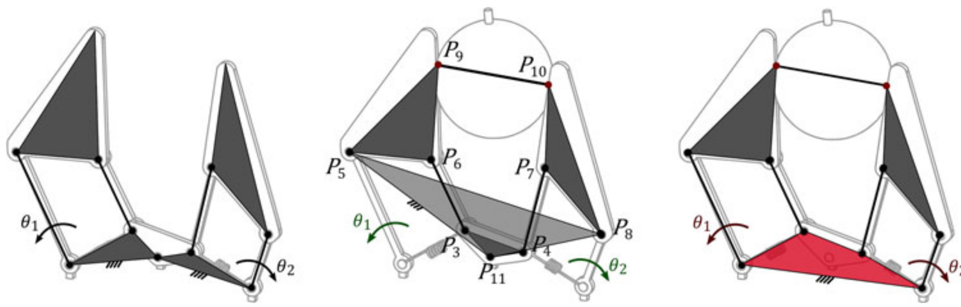

Fig. 5. In the approaching phase to grasp an object, a GR2 gripper behaves as a traditional two-finger gripper (left); once the object is grasped, the input angles θ_1 and θ_2 are fixed and the hand–object system constitutes a closed mechanism. In this kinematic chain, a $7/B_1$ Baranov truss, formed by the revolute joint centers $P_3, \ldots, P_{11}$, can be identified, and the rigidness of the grasp is geometrically guaranteed regardless of the condition of the tension springs (center). During in-hand manipulation tasks, the closed kinematic chain of the hand–object system corresponds to a 1-DOF Innocenti linkage with a quaternary link that passively modifies its geometry. Under the low-level control scheme of a GR2 gripper, this change of dimensions results from the tendency of the central triangular pivot to rotate toward the pushing direction (right). See text for details.

mercially available [9]; however, there are fundamental differences that make a GR2 gripper completely novel and different from those designs. For instance, other designs independently incorporate elastic elements in each finger for performing adaptive grasping operations. Explicitly, each finger corresponds to a five-bar linkage with two concentric revolute joints and another revolute joint preloaded with a spring that allows an enveloping grasp once an object contacts the proximal phalanx. In contrast, in the GR2 gripper topology, the elastic elements of the fingers are coupled through a pivot joint in order to improve the in-hand manipulation behavior of traditional two-finger robot grippers by passively changing the configuration of the base link after the initial grasp is achieved. Moreover, the introduction of the coupled springs does not affect the standard grasping operation of the gripper. To the authors' knowledge, this is the first time that the suggested structural topology for two-finger robot grippers has been proposed.

B. Low-Level Control Scheme

Control of two-finger robot grippers is generally accomplished via position control or force control, depending on the user requirements. Both fingers are commonly coupled and controlled using the same scheme. For in-hand manipulation, the GR2 gripper utilizes two actuators, one for each finger. Separate low-level control schemes can be implemented per finger.

In traditional two-finger robot grippers, maintaining stable grasping constraints on the object during in-hand manipulation requires the use of high-fidelity contact sensors and numerical algorithms to coordinate the fingers' motions relative to the object, thus limiting the practicability of such dexterous capability. In a GR2 gripper, a simple low-level position-torque switching control in each finger is implemented to avoid this disadvantage. During in-hand manipulation tasks, there is a pushing finger controlled via position control and an opposing finger controlled via torque control, so the constraint of the virtual binary link associated with the grasped object can be maintained without a coordination of the fingers' motion. The pushing finger directs the object motion, while the opposing finger serves primarily to maintain the contact constraints.

C. Grasping and In-Hand Manipulation With a GR2 gripper

Although the central triangular pivot in a GR2 gripper converts the fingers into five-bar linkages, making them underactuated in the classical kinematic sense by preloading the pivot with elastic members, we ensure that each finger converges to a minimal energy configuration from a single input. Hence, prior to contact with an object, the fingers of a GR2 gripper behave as independent four-bar linkages. In fact, as long as the actuation torques of the fingers are similar, the central triangular pivot tends to maintain its configuration, since there are no other factors affecting the equilibrium position. In this stage, a GR2 gripper acts as a standard gripper [see Fig. 5(left)]. Once the object is grasped, the input angles θ_1 and θ_2 are fixed and the hand–object systems constitute a closed mechanism. By following arguments similar to those used for the manipulation analysis of the traditional two-finger robot gripper, in this closed kinematic chain the seven-link linkage depicted in Fig. 5(center), formed by the revolute joint centers $P_3, \ldots, P_{11}$, can be identified. This kinematic chain indeed has mobility zero and corresponds to a $7/B_1$ Baranov truss [18]. As a consequence, the rigidness of the grasp is geometrically guaranteed regardless of the condition of the tension springs.

When a reorientation of the grasped object is performed (i.e., in-hand manipulation functionality), the closed kinematic chain of the hand–object system corresponds to a 1-DOF Innocenti linkage with a quaternary link that passively changes its geometry [see Fig. 5(right)]. Then, under the hybrid low-level control scheme, once the position-controlled pushing finger is moved to a new position, its revolute joint on the central triangular pivot tends to move in the direction of motion and an external pushing force is applied at the distal link of the compliant opposing finger with resultant forces acting along the lines defined by the proximal links. In consequence, as the tension spring of the opposing finger exerts a restoring elastic force, the central triangular pivot tends to rotate toward the pushing direction, thus changing the dimension of the quaternary link and modifying the geometry of the fingers.

In a GR2 gripper, the tension springs of the central triangular pivot directly affect the ability of the system to reconfigure the

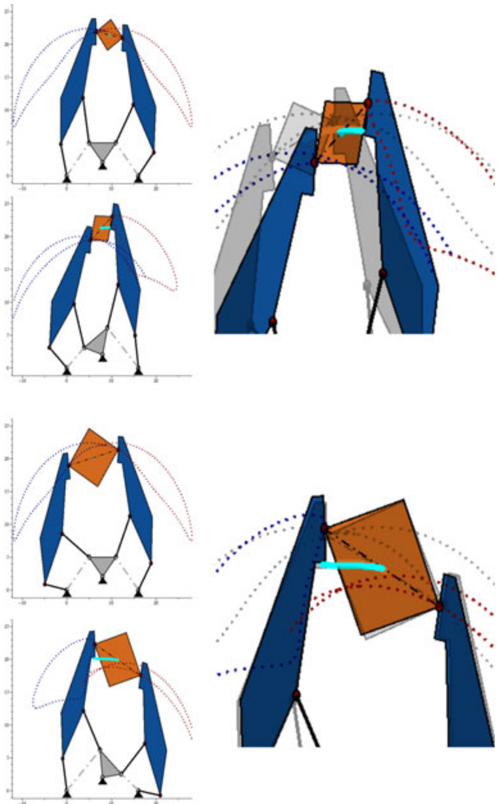

Fig. 6. Simulation of precision manipulations with a GR2 gripper based on the structural model of the hand–object system as a 1-DOF Innocenti linkage with a quaternary link of variable geometry. The sextic curve of each finger is depicted in the figures and the cyan (light) points correspond to the path traced by the center point of the line segment defined by the contacts. The final configuration of the traditional two-finger gripper (see Fig. 3) and that of the GR2 gripper are depicted as overlapped in the right side of each inset in grayscale and full color (digital version), respectively.

size of the quaternary link that constitutes the gripper's base. If these springs are infinitely stiff, the base link of the 1-DOF Innocenti linkage cannot be reconfigured and the mechanism behaves as a traditional two-finger robot gripper. In the absence of the tension springs, the geometry of the quaternary link is undetermined, since the central pivot is free to move. As rule of thumb, the tension springs should be selected with the minimum stiffness that allows the central pivot to overcome the friction in the revolute joints and return to its rest position.

Fig. 6 shows some simulation steps of a GR2 gripper performing a precision manipulation of two grasped objects—represented by rhomboid shapes—based on the model of the hand–object system as a 1-DOF Innocenti linkage with a quaternary link of variable geometry. The objects and initial configurations are the same as those used for the case of the traditional two-finger robot gripper (see Fig. 3). The simulation is kinematic and assumes that the length change on the tension spring of the pushing finger is equivalent to the rate change of the input angle. In the figures it can be observed how the sextic curve of each finger is modified during the manipulation with the cyan (light) points corresponding to the path traced by the center point of the line segment defined by the contact points.

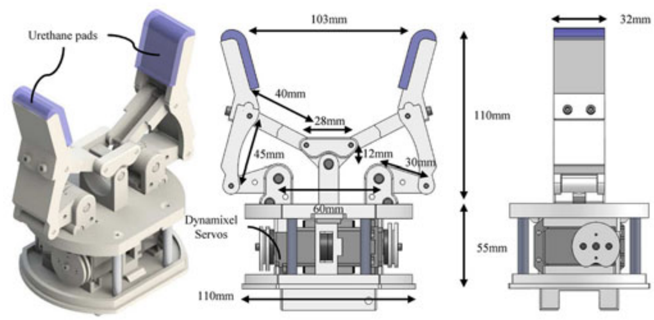

Fig. 7. Design overview of the GR2 gripper constructed to evaluate the proposed theoretical design; the dimensions of this example are comparable to commercially available two-finger robot grippers.

The final configuration of the traditional two-finger gripper (see Fig. 3) and that of the GR2 gripper are depicted as overlapped in the right side of each inset in grayscale and full color (digital version), respectively. With these examples, we illustrate the reorientation of grasped objects with a GR2 gripper, both clockwise and counterclockwise, and how the passive reconfiguration of the system can help to improve the range of reorientation achieved. Nonetheless, given the assumptions of the simulation and the overall in-hand manipulation analysis, the real benefits of the GR2 topology certainly remain to be verified by experimentation.

IV. In-Hand Manipulation Performance

A. Prototype Design Overview

A prototype of a GR2 gripper was constructed to evaluate the proposed theoretical design. An overview of this implementation can be seen in Fig 7. The actuator base and overall design parameters were adapted from the Yale OpenHand Project [19], an open-source design library for underactuated, 3-D-printed robotic hands. The structural components were 3-D-printed in ABS on the Stratasys Fortus 250 mc, a commercial desktop FDM printer. The distal fingertips were made detachable and modular to allow for testing different contact geometries, and the compliant pads were integrated into the finger structure via a multimaterial deposition process [20]. The revolute joints used press-fit steel dowel pins. The central triangular pivot could be either locked in place with clip-on linkages or preloaded with elastic bands for evaluating the performance of the gripper. In the implemented prototype, off-the-shelf orthodontic elastic bands were used as the tension springs described in the model (see Fig. 8).

B. Actuation and Control

Each finger was tendon-driven with a 21-mm pulley diameter attached to a MX-28 Dynamixel servo, which can produce a stall torque of 2.5 N·m at 12 V, the standard operating voltage for servos of this type. The tendons ran across the proximal joints, each with an effective 9-mm pulley radii, and terminated at the proximal link. Because the actuation scheme is single-acting, a torsional return spring was included at the base of each

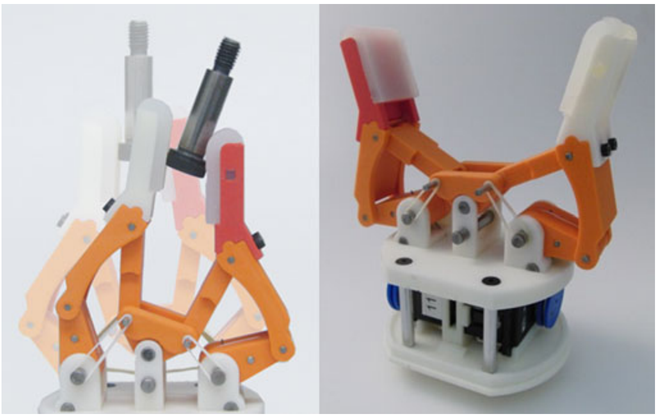

Fig. 8. Prototype of the GR2 gripper. In this implementation, the central triangular pivot could be either locked in place with clip-on linkages or preloaded with elastic bands. The distal links are detachable and modular.

finger. The holding grip force at the fingertips was measured to be 8.9 ± 0.35 N with a 25-lb load cell at a fingertip separation of 19 mm, and the gripper stroke is 0 to 103 mm. To prevent overheating, the servos' maximum torque output was capped at 40% of the stall torque, as suggested by the manufacturer. Using this limit gives us insight into the sustainable operating capabilities of the gripper, as opposed to just peak performance.

During standard operation, the servos were run in position control mode, using the Dynamixel's default on-board proportional integral–derivative controller. Since control of motor torque is not an operating mode available in these servos, the torque-control mode was achieved by setting a constant reference position, usually the maximum encoder position, while modulating the (software-set) maximum torque limit and ensuring that the encoder position set point was far enough away from the actual position to guarantee that the torque limit was being reached. This approach was shown to be sufficient for our purposes of in-hand manipulation; however, in application cases in which a precise torque control is required, the dynamics of the fingers should be taken into account and other more sophisticated torque-position transformers should be implemented [21] or drive systems with onboard torque control should be used. The authors would like to note that, due to the geared transmission in the servos used in the prototype, the commanded torque needs to be less than the desired output torque in practice. In this implementation of a GR2 gripper, the friction due to the transmission passively limits the speed of the system, which consequently helps to maintain grasp stability during in-hand manipulation.

C. In-Hand Manipulation Test

In order to evaluate the in-hand manipulation performance of the GR2 gripper concept, the achievable workspace for the implemented prototype with both locked and unlocked central triangular pivot was evaluated on the circular and square test objects of varying diameters shown in Fig 9. The square objects were also tested such that the finger pads were in contact with the object corners as opposed to their sides. According to the hybrid

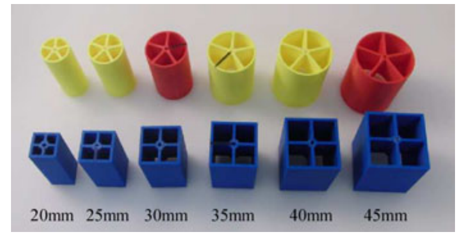

Fig. 9. Set of printed test objects used to evaluate the in-hand manipulation performance of the GR2 gripper prototype. The diameter/width varied between 20 and 45 mm. In all cases, the trakSTAR magnetic sensor was affixed to the object's center.

low-level control primitive, in the reorientation tests there was always a pushing finger and a compliant opposing finger. The pushing finger was driven in position-control mode and its goal position determined the reorientation direction. Once the object was grasped, the manipulation started by decreasing the torque output of the torque-driven opposing finger until the system went into motion. Once the pushing finger reached the defined goal position, the system returned the opposing finger back to position-control mode and locked the pinch grasp.

The test objects were instrumented with an Ascension trakSTAR sensor at their center to measure the displaced position and orientation. This 6-DOF magnetic tracking sensor provides a spatial resolution of 0.5 mm and 0.002 rad. From an initial pinch grasp, the GR2 gripper was moved to a target goal configuration and then back to the initial pinch grasp. The displacement was measured with respect to the initial pinch grasp pose in each move. The object was initialized such that the finger pads were in contact with the object where the fingertip curvature began, and the line between these contact points was parallel to the hand base. Given the slow-speed manipulation of the object, we assumed negligible effects from dynamics. If the object was ejected from the grasp during the transition, the data point was ignored.

In this way, we sampled the entire actuation space of the gripper. For each finger evaluated in its pushing state, we increased the commanded tendon position until the servo could no longer reach the commanded position due to either the actuator torque limits or mechanical limitations of the gripper's geometry. This methodology was repeated in three trials for each object in both the unlocked versus locked central pivot configurations. Fig. 10(left) shows the various test cases and shows how the behavior of the central triangular link could differ during manipulation motions.

D. Results

Fig. 10(right) shows a subset of the achievable workspaces of the GR2 gripper prototype for a variety of object sizes, measured across three trials per object. With the central triangular pivot unlocked and allowed to reconfigure, the gripper could achieve approximately the same Cartesian workspace for all tested object sizes, with objects displaced more along the z-axis in the locked case. However, with the central pivot locked, corresponding to the traditional design, the two-finger gripper could not achieve as large a range of reorientation for smaller objects, and

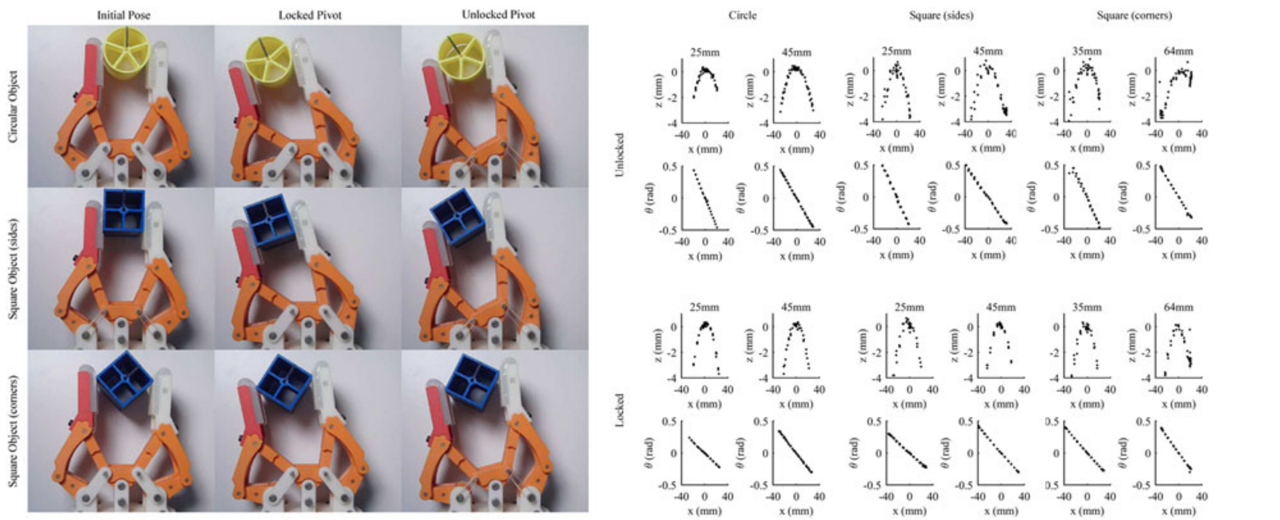

Fig. 10. (Left) Different test cases that were evaluated in the in-hand manipulation test. The square object was initially grasped with contact at its sides as well as its corners. The central triangular link can be locked in place or allowed to pivot. In the latter case, which corresponds to the GR2 gripper, the elastic bands ensure that the system resolves to a lowest energy configuration during experiments. (Right) Measured workspace for both unlocked and locked designs of the GR2 gripper prototype for some of the test objects. In general, the achievable orientation workspace is larger when the central triangular link is allowed to pivot.

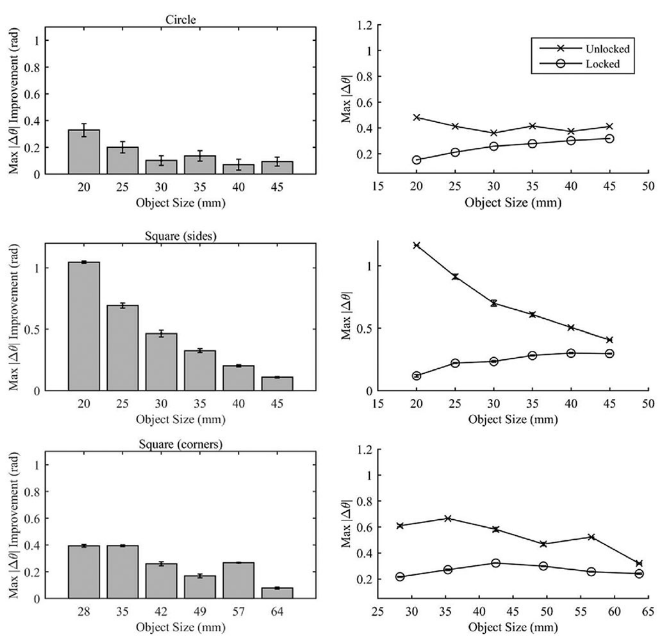

Fig 11. Measured improvement of the maximum achievable change in orientation from the initial pinch grasp configuration by using a GR2 gripper with an unlocked central triangular pivot.

the maximum achievable change in orientation ($\Delta\theta$) for each object was also decreased. This behavior is exemplified in Fig. 10(left), where the GR2 gripper manipulating different objects with unlocked and locked central pivots and identical actuation inputs is shown. The asymmetric trajectories in Fig. 10(right) are a consequence of hysteresis in the real-world system due to our use of tendon-driven actuation and our implementation of the simplified open-loop control scheme.

Fig. 11 further details the improvement in the gripper's reorienting capability with the addition of an unlocked central triangular pivot, in several cases exceeding 0.5 rad (28.6°) from rest. The multimedia extension of this paper (video) presents examples of the prototype manipulating test objects with the central triangular pivot both locked and unlocked.

For test cases involving the square object in which the initial contact is with the object sides, the contact conditions can favorably change when the central triangular pivot is unlocked. Whereas the finger pads maintain contact with the object sides throughout manipulation in the locked configuration, the contact can shift from the side of the object to one of the corners when manipulation with the central pivot unlocked. This behavior leads to a large improvement of the object's reorientation, as detailed in Fig. 11. An example of this characteristic can be seen in Fig. 10(left) as well as in the video extension. For test cases involving the square object in which the initial contact is with the object corners, no-slip contact conditions were difficult to maintain throughout the trials. As a result, the acquired data were much noisier than with the other test objects, as shown in Fig 10(right). Moreover, the manipulation trial was terminated earlier whenever the finger pads made contact with the object sides instead of just the corners because, in these cases, the object often could not be returned to its initial pinch grasp configuration as required by our protocol. Note that the same square objects were used for both side and corner contact cases; therefore, the effective object size, i.e., the distance between contact locations, is larger for the latter.

Anecdotally, we also noticed that the actuators drew more current with a locked central pivot, suggesting that an unlocked central pivot helped the system maintain a consistent contact with the object and avoid slippage. In practice, manipulation is highly dependent on the contact geometry and the point contact assumption made in the simulations of Figs. 3 and 6 is generally not the norm for the whole in-hand manipulation motion. Instead, rolling contacts are much more common, and also more difficult to maintain, with the flat finger pads used in this implementation of the GR2 gripper. The extra DOF afforded by the central pivot aids in overcoming the kinematic limitations of each individual finger. In the prototype used for these studies, the minimal number of elastic bands was used, just enough to ensure that the central pivot could overcome the friction in the revolute joints and return to its rest position. In this way, the minimal energy configuration maximizes motion in the central pivot and minimizes deformation in the compliant finger pads or slippage between the object and finger surface. This consequently makes the system less dependent on the contact conditions in real-world applications.

V. Conclusion

The GR2 gripper concept has been introduced in this study. The proposed underactuated gripper extends the capabilities of the traditional two-finger robot gripper by incorporating an enhanced predefined in-hand manipulation primitive that can be easily controlled, without knowing the size or shape of the object *a priori*. The in-hand manipulation behavior, namely, the planar reorientation of the grasped body, is predefined thanks to a simple hybrid low-level control scheme and is enhanced in comparison with the standard gripper, thanks to a simple novel modification in the topology of the traditional design: the introduction of an elastic pivot joint between the two fingers. Experiments with a prototype evaluating the in-hand manipulation performance demonstrate the reorientation behavior, verify the theoretical analysis of the system, and highlight the advantages of the improved gripper.

To the authors' knowledge, the GR2 topology for grasping and in-hand manipulation is presented and experimentally proved for the first time in this study. Given the generality of the concept, researchers and designers working on multiple areas of robotics can benefit from our findings, including those working on industrial robotics, prosthetics, teleoperation tasks, and home and service robots. Future work on the GR2 gripper concept could focus on topics of design optimization for specific ranges of reorientation, grip force, gripper stroke, or manipulation speed, to name a few. Those interested in optimally designing a GR2 gripper to be effective in a particular domain can find relevant optimization techniques in [10]. For this investigation, the authors did not adjust or modify the linkage lengths shown in Fig. 7. Another interesting area of exploration is the combination of the GR2 topology with adaptive grasping techniques for extending the pinch-grasping functionality to enveloping/encompassing grasps without losing the in-hand manipulation capability.

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