# An Underactuated Hand for Efficient Finger-Gaiting-Based Dexterous Manipulation

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***Abstract*— This paper presents a minimalist, four-finger hand comprised of two pairs of tendon-driven, underactuated fingers decoupled by an independent, central, rotating axis. This mechanical configuration allows for finger-gaiting while also retaining the passive adaptability and other capabilities of the underactuated finger pairs. As a result, the hand, requiring only four actuators, is capable of a unique set of dexterous manipulation primitives, including finger-gaiting and precision manipulation, while retaining the robust, adaptive precision and power grasping behavior of underactuated hands. The low-cost, compact design is built with rapid-prototyping techniques and off-the-shelf components, enabling quick and inexpensive fabrication that can be produced using even desktop FDM 3D printers.**

## I. INTRODUCTION

Enhancing robotic end effectors with dexterous capabilities has proven to be a difficult task despite extensive research [1-3]. The human hand has long been the standard to which robotic hands are compared, and as a result, many of the past attempts at achieving dexterity have been anthropomorphic, fully-actuated, and highly articulated. This high degree of complexity makes these hands unsuitable for many tasks outside of a well-controlled environment. Applications such as mobile manipulation or material-handling in unstructured environments motivate the design of simple, compact, and robust hands [4].

It has been shown that underactuated graspers are adept at passively obtaining stable power grasps in the absence of sensor feedback [5,6]. Furthermore, the use of differentially-actuated tendons and compliant flexure joints in place of conventional, direct-drive pivot joints increases the robustness of the hand in the presence of positioning errors or unexpected collisions. Past reviews of robotic and human dexterity remind us that manipulation is object-centric [1,7,8] and can be independent of the method by which the object motion is achieved. Dexterity is not necessarily restricted to redundantly-actuated systems with articulated, rigid-link fingers and well-defined point contacts throughout the task. There exist many robotics applications where users do not need to move an object arbitrarily in all 6 degrees of freedom within the hand workspace, and instead only need the hand to perform a few specialized and repeatable tasks very robustly [4,9]. For these reasons, we see the need for further exploring the dexterous capabilities of simple grippers through nonconventional means.

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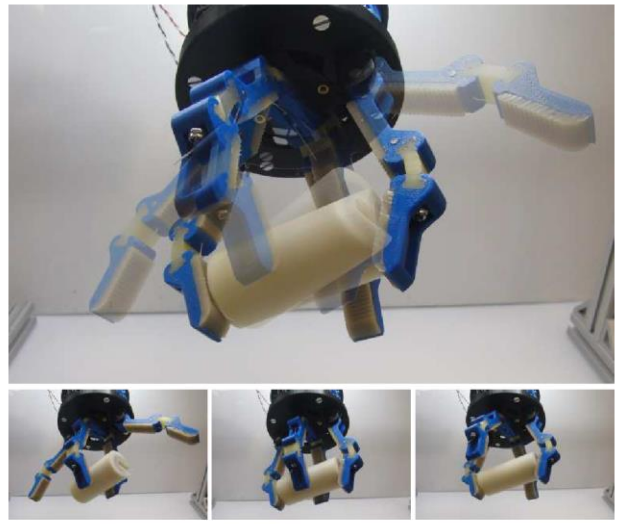

Figure 1. The underactuated, four-fingered hand with central rotary joint

In this paper, we present a hand comprising of two independently-controlled finger pairs that can rotate relative to each other, as shown in Fig. 1. Two independent sets of fingers allow for finger-gaiting by alternating grasps on the object, such that finger contacts do not need to be maintained throughout the entirety of a manipulation task. Although this type of finger-gaiting, which could also be described as in-hand regrasping, is just a single example of dexterous manipulation [2], it leverages the adaptability of underactuated fingers to assist in maintaining the stability of the object as it transitions between finger pairs. We also utilize design principles from previous work [6,10] to keep the hand low-cost and simple to fabricate, via desktop additive-manufacturing machines and off-the-shelf components.

## II. RELATED WORK

The majority of work related to the development of dexterous robot hands has focused on highly-articulated hands, typically attempting to mimic aspects of the anthropomorphic hand configuration. Examples range from the three-finger Stanford/JPL [11] and four-finger MIT/Utah hands [12] from the early 1980's to more recent designs, such as the Robonaut Hand [13] and DLR hand/arm system [14]. The complexity of these hands necessitates tendon-driven actuation systems placed outside of the hand itself. In-hand manipulation is limited by the contact constraints required to maintain a stable grasp on a given object [2,15]; therefore, many hand designs can only impart a limited displacement or rotation on the object relative to its initial, grasped configuration. For this reason, the ability to finger-gait: breaking and establishing new contact constraints while

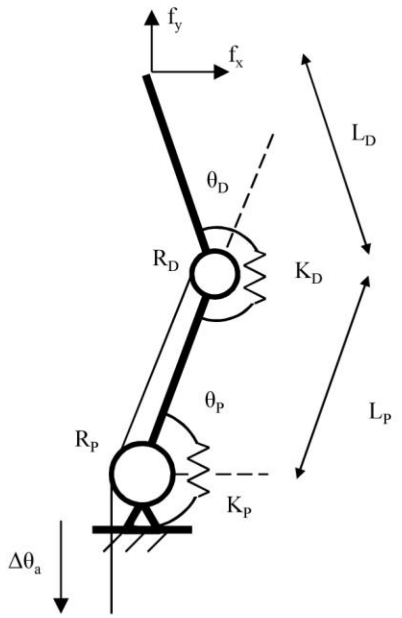


Figure 2. Model of a conventional two-link, underactuated finger used in this hand design, reproduced from [16]

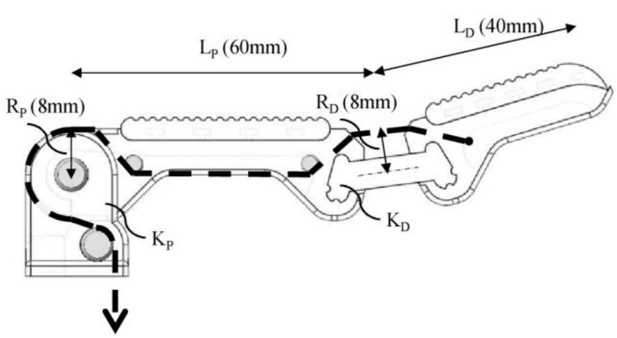


Figure 3 Physical model of the underactuated finger with revolute proximal joint used in the precision-grasping pair. The dashed line represents the tendon routing path.

maintaining a stable grasp on the object is critical. This often necessitates a high degree of mechanical complexity and coordinated control [1].

The defining features of the hand described in this paper are the rotational degree of freedom between the two finger pairs around the axis normal to the palm center, allowing them to rotate with respect to one, and the two underactuated finger pairs, each with different kinematics and functionality (Fig. 1). By rotating the bases of the finger pairs with respect to one another with a common rotary joint, we avoid more complicated designs in which each of the fingers must have an ab/adduction degree of freedom to enable similar motions. Conventional hands also incorporate rotational degrees of freedom normal to the palm, but these hands often have rotary joints at the base of many of the fingers, rotating orthogonal to the proximal joint [17-19]. This layout is predominantly used to transition the hand between a power-grasp configuration, where the fingers can interlace, and a spherical pinch-grasp configuration, where the fingers are spaced evenly apart [20].

To our knowledge, the basic concept of a central rotational axis was first implemented in Higashimori et al. [21] as a “dual-turning mechanism” to allow similar finger-gaiting behavior. While the rotational joint in the palm of the described work is similar to [21], the hand described in this paper has much simpler kinematics and mechanical complexity while retaining much of the novel functionality, namely twisting without releasing and regrasping. It implements this functionality with only four actuators compared to ten in the above work. Our hand can also utilize much simpler control methodologies due to passive compliance and underactuation.

The presented hand has four underactuated, two-link fingers, each with passively compliant proximal and distal joints. Their performance is well characterized in literature [22,23], and their design parameters in this hand are shown in Fig. 2. Equations 1-6 describe their behavior. Since there are more degrees of freedom than actuators, their behavior is determined by a combination of actuation input, internal passive compliance in the system, and contacts with objects and the environment, making the selected design parameters important to achieve the desired operation. In general, for a given input torque, the finger links will continue to close until they make contact or reach a joint limit.

$$-K\Delta\vec{\theta} + J_C^T\vec{f}_e + J_a^T f_a = 0 \tag{1}$$

$$0 = r_a\Delta\theta_a - J_a\Delta\vec{\theta} \tag{2}$$

$$J_a = [r_P \quad r_D] \tag{3}$$

$$J_C = \begin{bmatrix} -L_P\sin(\theta_P) - L_D\sin(\theta_P+\theta_D) & -L_D\sin(\theta_P+\theta_D) \\ L_P\cos(\theta_P) + L_D\cos(\theta_P+\theta_D) & L_D\cos(\theta_P+\theta_D) \end{bmatrix} \tag{4}$$

$$K = \begin{bmatrix} k_P & 0 \\ 0 & k_D \end{bmatrix} \tag{5}$$

$$\vec{f}_e = [f_x \quad f_y] \tag{6}$$

Although underactuated fingers are used in several commercial applications [17,18], they are not typically considered for use in dexterous tasks, as the system Jacobian is non-invertible. However, in cases where the system parameters allow for the fingers’ passive compliance to satisfy the grasp stability constraints, *n* actuators can move a grasped object in *n* degrees of freedom, with the remaining degrees of freedom determined by elastic averaging of the compliant elements in the system [24]. This has been validated experimentally in both planar [25] and spatial cases with these same classes of underactuated fingers.

Researchers have also shown that tabletop surfaces and environmental constraints can be used to reduce the effective degrees of freedom in the system, enabling underactuated fingers to perform repeatable precision grasps on very small items [26,27]. Similar constraints can be built into the hand itself and used selectively, such as the case of the lateral grasp [28], where the sides of non-moving fingers are used as stiff bracing surfaces. Our hand seeks to exploit these novel aspects of underactuated finger mechanisms, which have already been shown to be effective in open-loop grasping, for use in dexterous tasks.

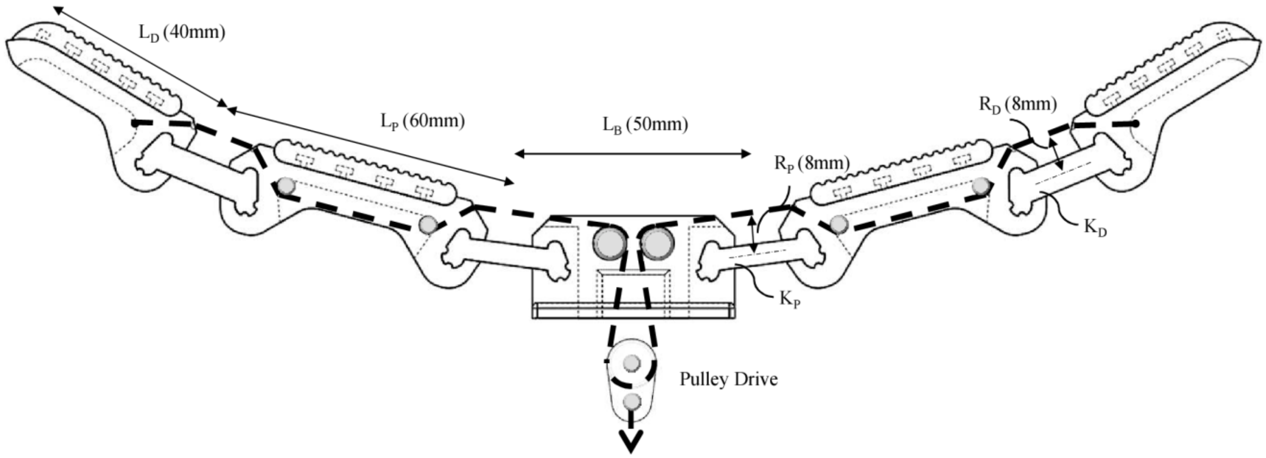


Figure 4. Physical model of the differentially-driven power-grasping pair, with flexures at the proximal joint.

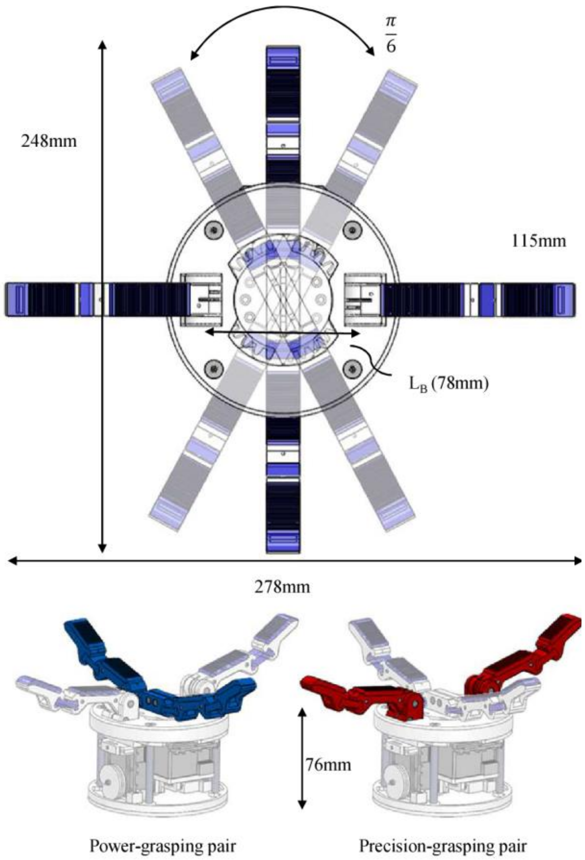


Figure 5. Geometric overview of the four-fingered dexterous hand

## III. Hand Mechanism Design

### A. Hand Structure

The hand is comprised of two finger pairs: a differentially-driven *power-grasping pair* with flexure-based proximal joints (for better adaptability to the object surface), and an independently driven, *precision-grasping pair* with pin-based, revolute proximal joints (for increased stability during pinch grasps and precision manipulation). Replacing the proximal flexures with a pin-based revolute joint minimizes parasitic motion due to out-of-plane compliance.

In terms of the general finger design, Fig. 3 and 4 show how this hand design implements the theoretical design parameters for underactuated fingers. Fingers for both the power-grasping and precision-grasping pairs utilize guidelines established by the Yale OpenHand Project [10], also consistent with previous work [25,26,28]. The proximal-distal linkage ratio ($L_P/L_D$) is 1.5, similar to human fingers. If modeled as a traditional finger with revolute joints, the transmission radius ($R_D$, $R_P$) of each flexure joint is approximately equal to the orthogonal distance between the midline of the flexure, the effective joint center, and the tendon entry point. The transmission ratio ($R_P/R_D$) was set at 1, due to empirical results from past work [16]. It should be noted that for flexure joints, the effective transmission radius decreases as the joint angle increases. The distal joint is set approximately 2.5 times stiffer than the proximal joint to help ensure that the proximal link makes contact with the grasped object before the distal. Both pairs of fingers in the hand implement approximately the same joint stiffnesses.

The power-grasping pair was design to perform much like the early planar versions of the SDM hand [6] with compliant flexures at both the proximal and distal joints. The two fingers have identical dimensions and were printed as a single piece, to be differentially driven by the drive pulley as shown in Fig. 4. The actuation force is balanced between the two fingers, allowing the pair as a whole to passively adapt to the grasped object's shape.

The precision-grasping pair utilizes more traditional revolute ("pin") proximal joints preloaded with a torsion spring. The revolute joint minimizes out-of-plane and off-axis compliance and increases the stability of precision fingertip grasps. Each finger is driven independently, which allows the pair to perform planar, in-hand manipulation [25].

The power-grasping pair is nested within a 28-tooth main gear constrained to rotate within the outer top frame, as shown in Fig. 5. This is driven by an offset, 12-tooth gear. This configuration allows $\pi/3$ *(60°)* of relative rotation between the two grasping pairs. Overall, the hand base has a diameter of 115mm and height of 76mm, and the hand as a

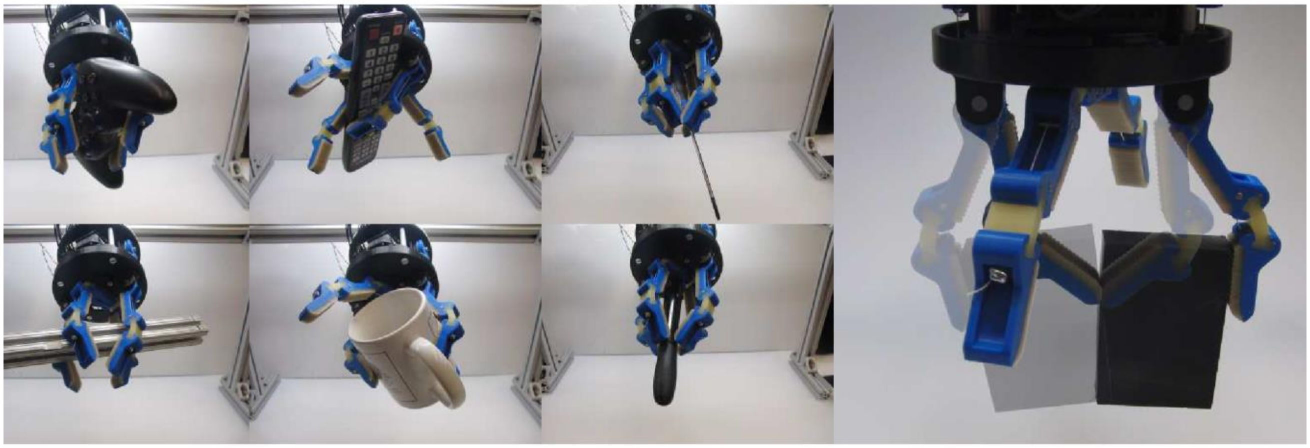

Figure 6. Examples of the hand's adaptive power-grasping and in-hand manipulation capabilities. The hand retains the adaptive, compliant behavior of previous underactuated designs [10,28]

whole currently has a cumulative weight of 685g, comparable to commercially available hands. The size and weight can both be reduced through further design refinement.

### B. Fabrication and Assembly

The fingers were produced via a combination of additive 3D-printing and material deposition, described in more detail in [10]. The main hand body, finger linkage bodies, and outer mold shells for the flexure joints and fingerpads were 3D-printed on a Stratasys Fortus 250mc with layer height 0.178mm. The flexure joints were made by pouring the two-part PMC®-780 rubber urethane [29] and two-part Vytaflex® 40 urethane [30] into the joint and pad cavities, respectively. After curing, the thin mold walls were removed to expose the joints and pads. Small protruding, anchoring features were added to the finger link body geometries to ensure that both urethanes remain attached to the finger bodies [10].

We used accessible off-the-shelf parts for the remaining hand components. The tendons, 100-lb test Spectra® fishing line (polyethylene), are routed across steel dowel pins to prevent abrasive wear and tear on the printed ABS surfaces. For actuators, we selected four Robotis MX-28 Dynamixel servos, each with a stall torque of 3.1 N-m (at 14.8V). The actuator frames also serve as structural supports in order to minimize part count and make the design accessible for future improvements.

## IV. Manipulation Capabilities

Fig. 6 shows both the finger pairs' abilities to achieve performance validated in past work with underactuated hands [6,25]. Each pair can be used independently of the other in tasks best suited for that particular pair. In combination, each pair is no longer limited by the workspace of its component fingers, and the hand can achieve a novel set of manipulation primitives:

### A. Pinch-to-Power Gaiting

Hand pre-shaping and positioning prior to securing an object is often critical to a successful grasp acquisition, as most hands cannot continue to manipulate the object after achieving a grasp. Poor planning, even with passively adaptive hands, can result in a weak and unstable pinch grasp. It would be beneficial to increase the number of contacts and transition the object into a more secure, enveloping-grasp configuration from the initial pinch grasp [16]. In the absence of gaiting, controlled slip would be necessary for such transitions. The release of a grasped object can only occur along the edge of the hand workspace [25], since underactuated fingers cannot independently control force output and fingertip trajectory.

However, in this hand, the power-grasping pair can be used to secure the object in place while the precision-grasping pair "resets", or "rewinds," to perform another caging motion and continue transitioning the object toward the palm and an eventual power-grasp (Fig. 7). The adaptability of the power-grasping pair helps to minimize unintended perturbations from the object trajectory determined by the precision grasping pair. The out-of-plane stiffness of the proximal joints in the precision-grasping pair make it more reliable for pulling the object inwards into the palm while avoiding ejection or undesirable twist-out cases.

### B. Continuous In-Hand Twisting

By alternating grasps on the object and interspersing them with rotations of the central joint, the hand can achieve a continual twisting motion on an object, as shown in Fig. 8. This task is not necessarily limited to radially symmetric objects, as the out-of-plane compliance of the power-grasping pair can aid in securing irregular objects during grasp transitions. The rotational motion is completely decoupled from that of the fingers and does not require any coordination among the other actuators but is limited by the torque output of the central rotary joint. While a twisting motion can be imparted on an object with a simple gripper and capable arm by repeated re-grasping, this hand can perform the task while maintaining a stable grasp on the object at all times, which can be helpful in circumstances and environments when the object cannot be reliably released between turns.


Figure 7. Example of a pinch to power manipulation primitive


Figure 8. Example of an internal twisting manipulation primitive. Note that a grasp is maintained on the object at all times.

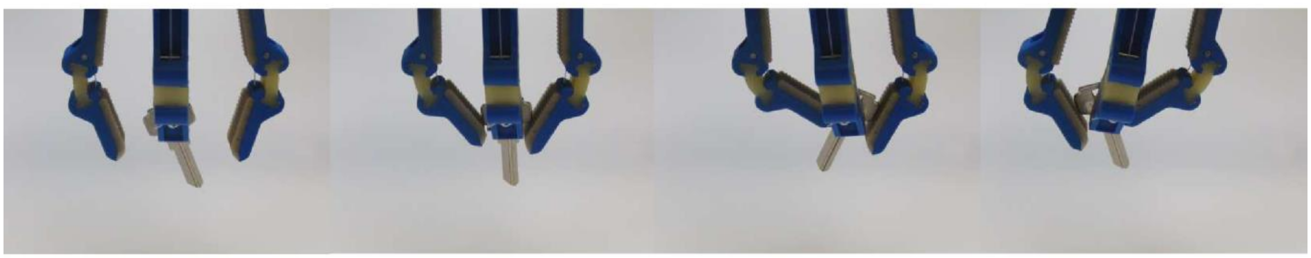


Figure 9. Example of a finger-pivoting manipulation primitive, reserved for fine re-orientation of small objects in a pinch grasp. The power-grasping pair establishes a virtual pivot through the base of the key, and the key's rotation is driven by the precision-grasping pair

### *C. Finger-Pivoting/Tracking*

The power-grasping pair can be used to establish a virtual axis of rotation on the object, while the other pair is used to rotate the object about this axis [31]. Fig. 9 shows an example of this manipulation primitive with the hand re-orienting a key within a pinch grasp. The off-axis compliance of the power-grasping pair's proximal flexures accommodates the perturbations imparted by the precision-grasping fingers while maintaining a stable pinch grasp.

## V. Conclusions and Future Work

In this paper, we presented a dexterous hand consisting of two pairs of underactuated fingers coupled by a central rotary joint. While this design structure is not unique, it is particularly well-suited for underactuated fingers due to their inherent ability to passively obtain adaptive grasps. This allows for robust, albeit simple, finger-gaiting and in-hand regrasping, and enhances the capabilities of the hand, even in the absence of extensive feedback. We provided many examples of unique manipulation primitives not otherwise possible with other hand designs of similar complexities.

This four-fingered hand design attempts to encourage further non-traditional forms of dexterity, since conventional approaches to finger-gaiting with redundantly-actuated systems have remained difficult to implement due to their high cost and complexity. Much simpler mechanisms with a proper selection of design parameters can result in equally, if not more, robust execution of manipulation tasks.

Future work will center on a more thorough exploration of the design space, especially with respect to asymmetric configurations. In this hand, the central rotary joint and similar fingers were selected largely due to convenience and hand packaging constraints, but the passive reconfiguration of the system during tasks, especially during grasp exchanges, should differ considerably depending on the individual fingers' and finger pairs' relation to each other. We aim to continue to iterate upon robust and functional hand designs through these methodologies.

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