M^2 Gripper: Extending the Dexterity of a Simple, Underactuated Gripper

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Abstract In the development of robotic hands, researchers have sought to increase inherent functionality without incurring greater complexity and cost. In this paper, we extend the manipulation capabilities of a simple gripper through a novel, underactuated design that produces several distinctive modes of operation. The proposed asymmetric hand design, the Multi-Modal (M^2) Gripper, consists of a modular thumb with varying degrees of passive compliance and a dexterous, tendon-driven forefinger that can produce either underactuated or fully-actuated behaviors. With only two actuators and basic open-loop control, the hand is able to adaptively grasp objects of varying geometries, pinch-grasp smaller items, and perform some degree of in-hand manipulation via rolling and controlled sliding. We also detail the properties of this hand morphology that make it well-suited for future work in medical applications, haptic exploration, and studies on controlled stick-slip manipulation tasks.

Keywords underactuated hand, modular, mechanical design

1 Introduction

Basic grippers are appealing due to their low-cost, mechanical minimalism, reliability, and simple control schemes. However, most, especially those in industrial applications, are designed for securing a limited range of objects to the end of a manipulator. At the other end of the spectrum, highly "dexterous" effectors utilize significantly more actuators in an attempt to mimic the functionality of the human hand [1]. The increased complexity required in these hands make them difficult to use outside of a controlled, closed, research environment [2]. Applications in mobile manipulation require robotic hands in between these two extremes: robust and durable enough to endure the conditions in unconstrained environments but also capable of more than simple pick-and-place tasks.

Underactuation and the use of passive elements to increase the inherent "me-

Fig 1. Rendering of the proposed gripper with multiple operating modes. Weight of gripper is 430g.

chanical intelligence" of hands have been presented as ways of increasing a hand's set of achievable tasks while minimizing additional weight and cost. Tuning the mechanical design parameters of the system and/or introducing additional passive elements can optimize the reconfiguration of the system under a range of operating conditions. This design approach has been shown to be particularly effectively in adaptive power-grasping [3] and has been included in several commercial hands [4-5]. However, the inability to actively control all degrees of freedom makes it difficult to plan repeatable precision manipulation tasks even with full knowledge of the system state [6].

For precisely modulated, safety-critical manipulation, underactuation may result in a level of uncertainty that is unwelcome for particular tasks and application areas. For example, the da Vinci surgical system utilizes only forcep-like 1-DOF grippers on articulating wrists. Manually-controlled, mechanical laparoscopic graspers also resemble simple forceps, though a non-articulating thumb is present in some designs [7]. To compensate for underactuation, relevant past work has utilized extrinsic forces and reliable, static features in the environment to constrain the hand and reduce the number of free degrees of freedom [8-10], suggesting that it would be useful to transition from an adaptive, underactuated configuration to a fully-actuated one when performing more dexterous tasks. The extension of dexterity in a sensor-equipped hand also provides additional potential for enhanced haptic perception, via the exploratory procedure framework of [11].

Underactuated hands can be considered as an "intermediate solution between robotic hands for dexterous manipulation and simple grippers" [12]. In this paper, we present a versatile, underactuated gripper that bridges this gap. The M^2 Gripper can switch between multiple operational modes, allowing it to achieve both the adaptive, shape-enveloping characteristics of [12] and predictable motion primitives necessary for in-hand manipulation [11]. This manipulation, which may involve repositioning objects of various sizes and shapes through rolling and sliding, is easily

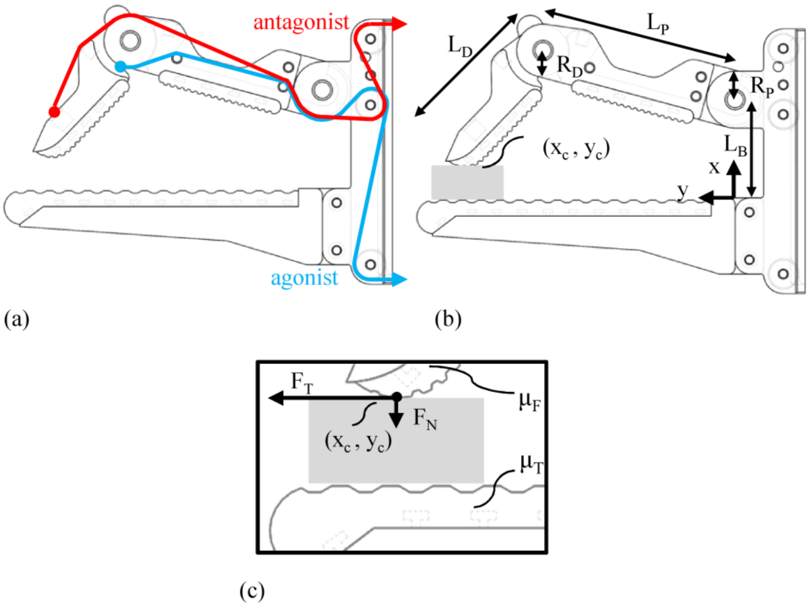


Fig 2. (a) tendon routing of the gripper, (b) details of the kinematic structure, and (c) a closeup of the forces acting on the object

achievable via simple actuation patterns. Varying the modular thumb design and material properties can also introduce custom-tailored behaviors for specific tasks. This hand design, shown in Fig 1, extends our existing, open-source, modular framework [7,13] and a prior biomimetic gripper design proposed for haptic manipulation tasks in surgery [14]. The M^2 Gripper concept is meant to enhance the compactness and simplicity of a basic gripper with more dexterous proficiency, allowing for a larger variety of achievable tasks with minimal additional control or hardware overhead.

2 Mechanical Hardware

2.1 Overview

This hand builds on an existing underactuated design from the Yale OpenHand Project [7] that originally had two underactuated, tendon-driven, two-link fingers each independently actuated by a hobby servo. In the current M^2 Gripper design, the two underactuated fingers have been replaced by an interchangeable static thumb and a modified two-link forefinger driven by two tendons. Depending on whether or not both actuating tendons are engaged and active, the forefinger may be underactuated or fully-actuated, giving the hand a set of different behavioral profiles.

A mechanical description of the system is presented in Fig 2. An *agonist* tendon routes across the front of the proximal and distal joints, and is anchored at the distal link, while the *antagonist* tendon routes across the front of the proximal joint in parallel with the agonist tendon but then runs across the back of the distal joint, anchoring at the back of the distal link. When actuated independently, the agonist tendon causes both finger links to close inwards, while the antagonist tendon pulls the distal link outwards. Both tendons actuate the proximal joint in the closing direction, ensuring that a positive normal force is applied to the grasped object when either tendon is engaged. Mechanical hard-stops at each joint ensure that both joint angles remain non-negative.

2.2 Fabrication

As an extension of the OpenHand project, the M^2 Gripper components were built via a combination of 3D-printing and casting techniques [7]. 100lb test Spectra line was used for the actuation tendons, and these were routed across nylon pulleys at the base of the fingers and across steel dowel pins within their body linkages. The rubber urethane fingerpads were deposited into sacrificial mold features, with a thorough description of the fabrication process for the fingerpad elements described in [16]. Either elastic bands or extension springs can be used to reset the finger configuration when the actuation tendons are slack. Both joints exhibited an approximate stiffness of 44 mNm. Consistent with existing designs, the hand utilized a linkage ratio (L_p / L_d) of 1.5 with combined forefinger length 100mm and a transmission ratio (R_p / R_d) of 1.0 [3,17].

3 System Model

One of the primary goals in developing this gripper design was to implement a linear "tracking" motion for the forefinger along the length of the thumb, as described in [14]. This motion, where one fingertip traces along the surface of the opposing finger, can aid in haptic exploration as well as pinch-to-power and power-to-pinch transitions [18]. This requires an analysis of the controlled slip problem, a review of which can be found in [19]. Fig 2c summarizes the key characteristics of the object-centric view of this problem. For controlled slip, the primary focus is on the system conditions where either the forefinger-object or thumb-object contact begins to slip (|F_T |>μ|F_N |).

The behavior of underactuated fingers is a well-studied problem [20,21], and the actuation of the forefinger tip (x_c, y_c) in this system can be described by the following relations (with the minimal effect of the joint stiffnesses disregarded for simplification):

$$f_a = \begin{bmatrix} f_{agonist} \\ f_{antagonist} \end{bmatrix} \quad (1)$$

$$J_A = \begin{bmatrix} R_P & R_D \\ R_P & -R_D \end{bmatrix} \quad (2)$$

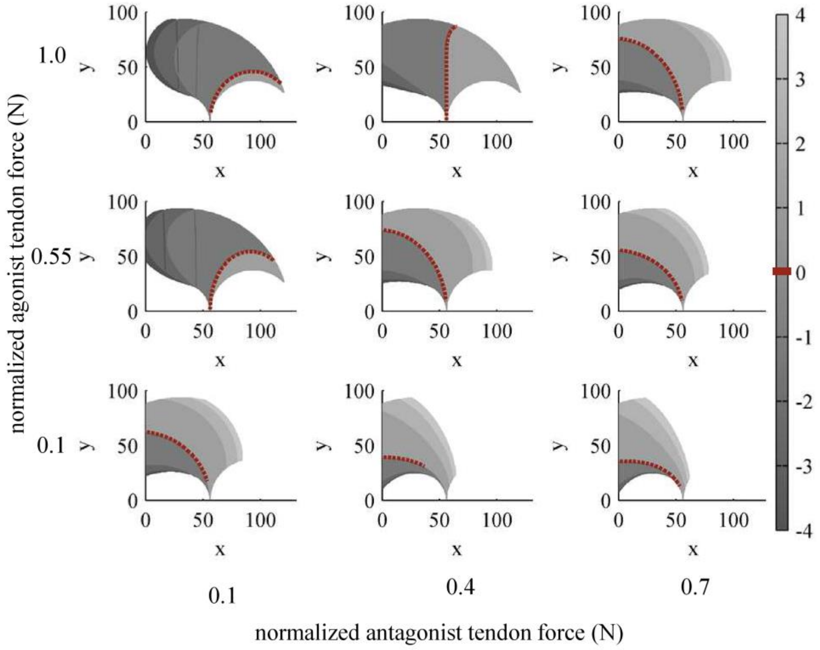


Fig 3. Slip conditions for combinations of actuation tendon force in the workspace of the gripper. *x* and *y* refer to the axes illustrated in Fig 2b, at the base of the static thumb. Dotted line marks the transition between *push-out* and *pull-in* behavior. The plotted coefficient of friction (F_T/F_N) equals the static coefficient of friction necessary to prevent slip at the forefinger tip.

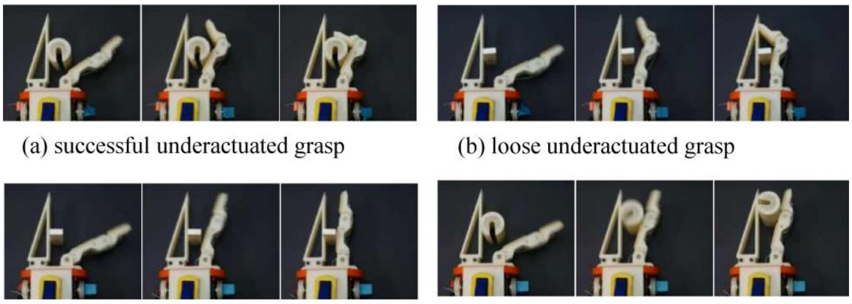
$$f_e = \begin{bmatrix} -F_N \\ F_T \end{bmatrix} \tag{3}$$

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

$$\tau = \begin{bmatrix} \tau_P \\ \tau_D \end{bmatrix} = J_A f_a = J^T f_e \tag{5}$$

Equation (5) summarizes the general characterization of a two-link, fully-actuated finger. The actuation Jacobian J_A maps the tendon actuation forces to the effective proximal and distal joint torques, τ_P and τ_D, respectively. The fingertip forces F_N and F_T with respect to the opposing surface, as shown in Fig 2c, are then calculated using the standard finger Jacobian J.

These relations can be mapped to the entire Cartesian and actuation workspace of the forefinger to provide additional insight, as shown in Fig 3. Each subplot shows the reachable workspace of the forefinger tip (x_c, y_c) for a given pair of actuation tendon forces such that the output normal force F_N remains positive. The range of sampled tendon forces in Fig 3 was arbitrarily selected to show the useful, functional limits of the actuated forefinger. The contours in each subplot denote the ratio $\mu_F = F_T/F_N$, or the minimum coefficient of friction necessary to avoid slip at the forefinger-object contact. For these motions, we assume a low co-



(a) successful underactuated grasp (b) loose underactuated grasp

(c) successful fully-actuated precision grasp (d) unstable fully-actuated grasp

Fig 4. Difference between (a-b) underactuated grasping, when only the agonist tendon is actuated and (c-d) fully-actuated grasping, when only the antagonist tendon is actuated and the distal joint limit is engaged

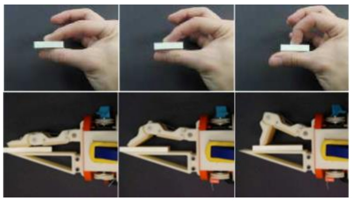


Fig 5. Example of the robot hand's ability to pull-in and push-out objects via sliding against the static thumb, inspired by a human manipulation strategy to execute pinch-to-power and power-to-pinch motions

efficient of friction at the thumb-object interface. Since F_N is nonnegative, a positive ratio indicates a push-out motion, and a negative ratio indicates a pull-in motion. Fig 3 shows that actuations of the agonist and antagonist tendons produce pull-in and push-out behaviors, respectively. Unlike a fully-actuated finger, allowing either tendon to run slack produces unique and useful behaviors, described in further detail in the following Section.

4 Performance

The M^2 Gripper is capable of several modes of operation via a simple open loop control scheme based on four states of agonist and antagonist tendon tension. These modes comprise fully actuated and underactuated grasping in addition to in-hand object manipulation in pull-in (distal) and push-out (proximal) directions.

4.1 Grasp Acquisition

In underactuated grasping [3,21], the two links of the finger are coupled by the agonist tendon leading to a conventional underactuated trajectory and power distribution. In the fully-actuated precision-grasping scenario, tension in the antago-

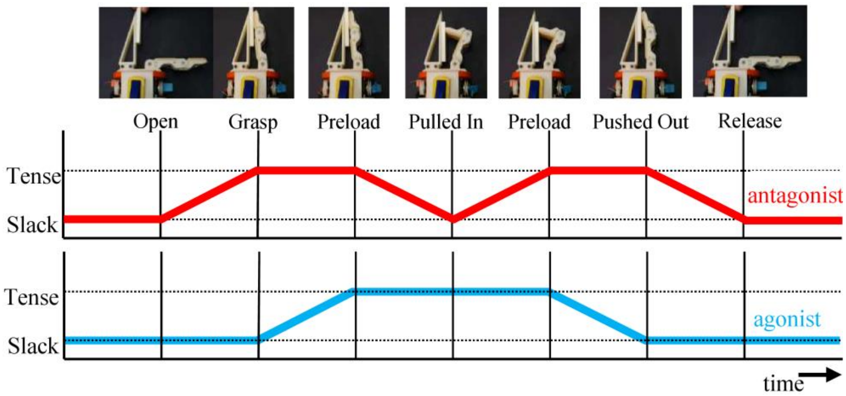


Fig 6. Open loop actuation profile for fully actuated grasping followed by the pull-in and push-out in-hand manipulation

nist tendon draws the proximal link inwards while locking the distal link against the mechanical hard-stop in a fully extended pose. This has the effect of reducing the degrees of freedom in the system to one. In each grasping case, the disengaged tendon is left slack.

Comparisons of the two grasp types for two objects are shown in the four motion sequences of Fig 4, where benefits and shortcomings of each mode are illustrated. In these examples the thumb surface is rigid and smooth, with a low coefficient of friction.

For a cylindrical object (diameter = 36mm) an underactuated grasp envelopes the object (Fig 4a) creating a stable grasp with three points of contact. A fully actuated grasp of the same object is shown in Fig 4d. This leads to the object being distally ejected and a non-stable grasp. A smaller rectangular object (8mm x 19mm) is not grasped in the underactuated case, as premature flexion of the distal link during closing leads the fingertip to contact the thumb before any contact has been made with the object. In the fully actuated case however, the reduced DOF allows the object to be stably pinched by the unconstrained motion of the proximal link.

4.2 Precision Manipulation

The further two modes of operation, which enable in-hand manipulation, are demonstrated in Fig 5 and Fig 6 using a low friction thumb. Once an object is held in a precision grasp using the antagonist tendon, tension is also applied to the agonist tendon until it is taut. Both tendons are now engaged and the system is in equilibrium, maintaining a contact force with the object. At this stage reduction in the antagonist tension leads to finger flexion due to the pre-loaded agonist tendon. This creates a lateral pull-in motion while maintaining a positive normal force against the object.

To facilitate a push-out of the object after the pull-in motion, both tendons are again engaged while the finger is under flexion. In this case, releasing tension on the agonist tendon causes the finger to return to full extension, due to the pre-

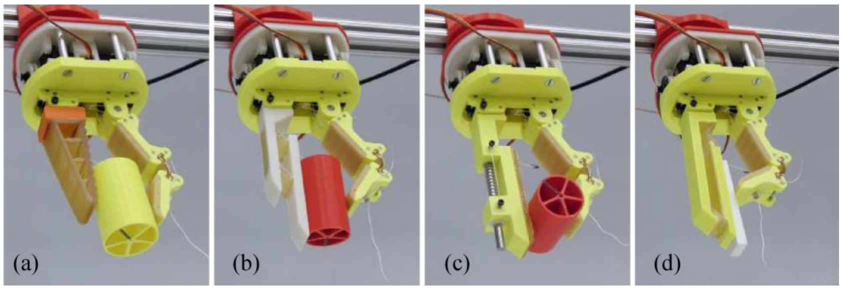


Fig 7. Examples of different interchangeable thumb designs that can be implemented for specific behaviors

tension on the antagonist (Fig 6).

Depending on choice of thumb structure or material, this actuation strategy may be used to enable object sliding relative to the thumb or forefinger, or for particular objects, rolling with no slip between the fingers.

5 Discussion and Applications

In [14], observations of exploratory hand motions by surgeons led to the initial design of an asymmetric gripper prototype for enhanced object palpation and manipulation in medical applications. This concept has been further developed via the selective underactuation of the M^2 Gripper, which provides a simple control method for selecting various grasp types and in-hand manipulation. Past work [15] has already proposed the use of underactuated grippers to aid in surgery, but only for grasp acquisition and extraction tasks. The M^2 Gripper allows similar enclosure and power-grasping of some tissue while also permitting precision grasping for more delicate operations. When fully actuated, it functionally operates like surgical forceps.

The M^2 Gripper's 2-DOF, tendon-driven actuation principle and relative mechanical simplicity suggest that RMIS (robot-assisted, minimally invasive surgery) compatibility is possible. In fact, the rigid jaws of da Vinci EndoWrist tools similarly implement two antagonist tendons for rigid finger articulation, with two additional tendons driving wrist flexion and rotation.

The ability of the proposed gripper to maintain contact and manipulate the object through controlled slip parallels the motions by which humans perceive various detailed haptic properties of objects [11]. A variety of anthropomorphic hand movements glean different types of haptic information from an object. Enclosing an object reveals volume and shape, lateral finger motion (rubbing/tracking) gives textural information, and squeezing/pinching provides feedback regarding stiffness [11,14]. Few practical grippers, particularly in the medical field, afford more than a single exploratory motion. With the M^2 Gripper, as in [8], such explorative manipulation is possible with only minimal a priori knowledge regarding the object.

Due to the manipulation ability of the forefinger in this hand, we believe that it should be possible to acquire significant haptic information from an object using only thumb-based sensors and procedures of active exploration, as proposed in [23]. This is in contrast to alternative sensing solutions, which either maximizes the area of sensor surfaces on the effector [22] or can only probe objects under the condition that the target object is not perturbed [24]. The interchangeability of the thumb in the M^2 Gripper would allow this to be easily tested.

6 Conclusion and Future Work

In this paper, we presented a simple, underactuated gripper with multiple modes of operation. We demonstrated the gripper's proficiency in applications requiring power and precision grasps and also highlighted its potential with regard to haptic exploration and controlled slip. As discussed, we have not yet optimized the mechanical design parameters of the system to improve its performance. Future work will focus on tuning the mechanical properties to increase the repeatability of the dexterous pull-in and push-out primitives described in Section 4. It would be beneficial to produce a degree of stick-slip behavior, where the forefinger can pull in and/or push out grasped objects via a repeated manipulation gait, whereas it is currently limited to a single pull-in or push-out motion.

The design choices for the passive thumb are also avenues for future research. Although it is not actuated, the thumb can be implemented with compliant truss structures or other elastic elements to modify its behavior during grasping and manipulation. Fig 7 highlights the ease by which custom thumb designs can be swapped in and out on the gripper. For example, the thumb shown in Fig 7a exhibit's a caging behavior on contact [25], and the thumb shown in Fig 7c with a linear degree of freedom simplifies the pull-in and push-out task primitives without relying on controlled slip. In our work with the M^2 Gripper, we noted that the use of softer fingerpad materials resulted in an effective coefficient friction that was force-dependent. The implementation of bistable or buckling components may also further increase the number of useful operation modes via our simple gripper design.

Acknowledgments The authors would like to thank Spencer Backus for his feedback in refining the mechanical design of the described gripper

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