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Underactuated Grasp Acquisition and Stability Using Friction Based Coupling Mechanisms

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Abstract—**Underactuated fingers have been extensively studied and optimized in order to achieve better grasp performance in terms of object acquisition and stability. However, little work has been done related to the coupling mechanisms between the fingers and their effects on grasp performance. This paper presents a novel method of underactuated finger coupling that utilizes friction and allows for increased stability and adaptability of robotic grippers. We show that variable friction within the coupling element can help the system maintain kinematic form closure while not affecting non-closure forces during grasp acquisition. A proof of concept prototype demonstrates the increased stability of objects within the grasp as compared to traditional coupling mechanisms.**

I. Introduction

Underactuated hands have fewer actuators than degrees of freedom. These systems are often referred to as adaptive due to the fact that the final configuration of the hand is a function of both the actuator position and external interaction forces with an object. These hands have numerous benefits over traditional fully actuated systems including simpler control, high adaptability to sensory and positioning error, durability, mechanical simplicity, and lower cost. Examples of underactuated robotic hands include [1-4].

While the advantages described above are significant, the nature of underactuated fingers and hands creates potentially undesirable properties for robotic grasping and manipulation. One of the most significant of these is the compliance of the mechanism in response to external disturbances or unbalanced forces. The same passive adaptability that allows the hand to comply to the object shape or other environmental constraints can also cause it to move or reconfigure after grasp. This is due to the combination of the unconstrained degrees of freedom of the mechanism and any joint compliance. Previous work by the authors has shown how this stiffness affects finger posture in the presence of external forces applied to the mechanism [5].

In this paper we describe how a simple friction-based mechanism can be applied to the transmission of cable-driven underactuated fingers/hands in order to increase the stability of underactuated grasps and improve disturbance rejection. We will discuss these mechanisms in the context of the grippers' ability to passively adapt to object size, shape and positioning errors as well as their ability to provide a stable grasp that can resist external (or inertial) disturbance forces once the grasp has been acquired.

We begin this paper with a description of the grasp acquisition process for underactuated hands. Next, we introduce models of our proposed friction-based coupling mechanisms and show how these can increase grasp stability. Finally, we present a generalized analysis of compliance and stability as a function of the constraints related to coupling schemes and describe design configurations that optimize hand performance related to these parameters.

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II. Methods

A. Grasp Scenario

Consider the simple task of picking up a coffee cup using a two finger robotic hand with adaptability between the fingers. First the gripper is positioned to place the coffee cup within the span of the fingers. Inevitably, positioning errors will result in an offset between the center of the gripper and the center of the coffee cup. As the fingers are closed, one finger will make contact before the other. The adaptive behavior of the hand will allow the second finger to continue traveling toward the cup with the first finger held in position by the contact against the opposite side of the cup. Since a stable grasp is not yet achieved, the contact forces of the first finger must be small enough not to move the object from its current position or tip it over [6]. After both fingers have made contact, forces increase at an equal rate until the desired grasp pressure is achieved.

Once the cup is lifted off the ground, it is desirable to have the cup maintain its position relative to the gripper in the presence of unbalanced contact forces or external disturbances – shifting of the object could cause it to be lost from the grasp. Current underactuated hands with typical coupling mechanisms will tend to center the coffee cup in relation to the gripper due to unbalanced contacts and finger compliance. The friction based coupling mechanism described in this paper will negate the centering effect and help keep the object in position if acted on by an external force.

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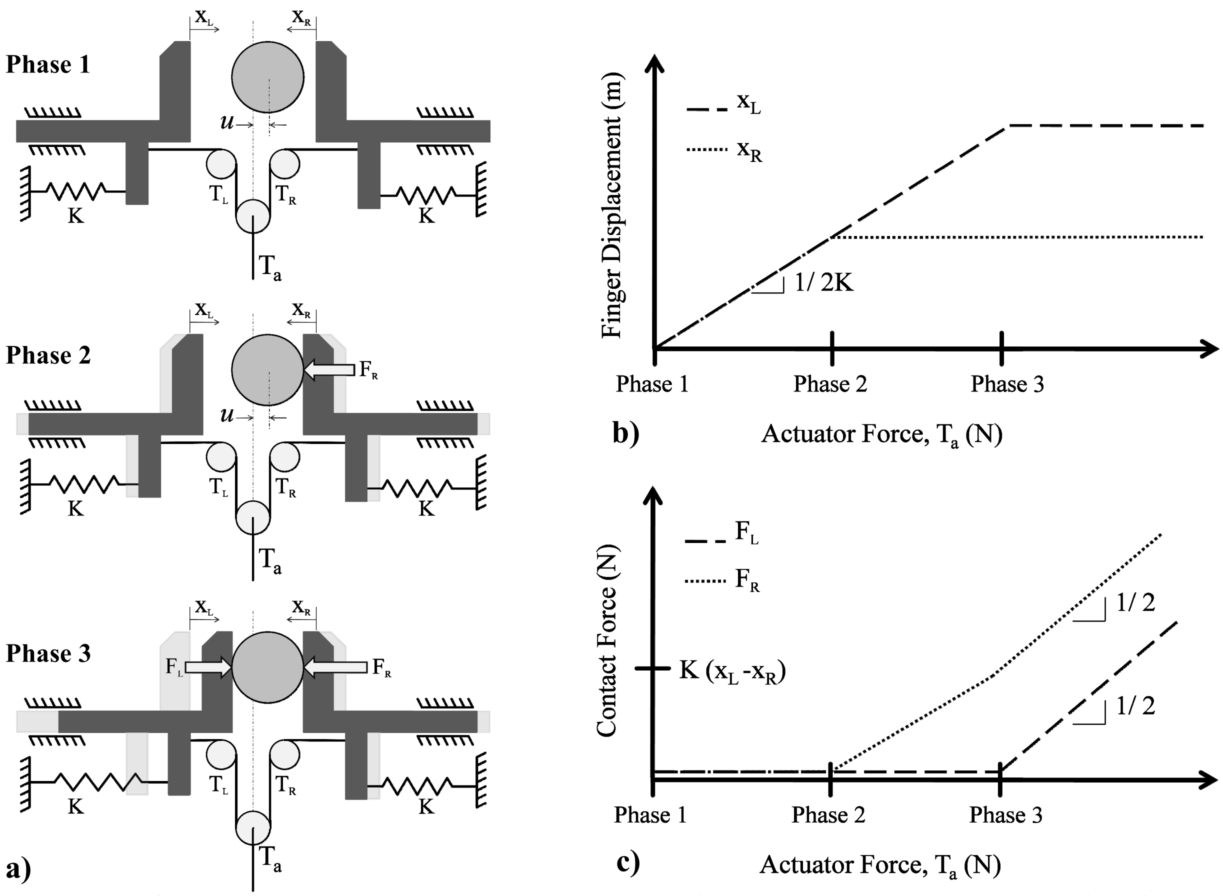


Fig 1. a) Phases of grasp acquisition in a two-DOF prismatic gripper. b) Finger displacements during grasp acquisition. c) Relationship between right and left contact forces during and after grasp acquisition. Here, K, represents the spring constant of each finger. Point P shows the location of the maximum non-closure grasp force.

B. *Prismatic Two-DOF Gripper*

A two-DOF prismatic gripper, shown in Fig. 1a, will be used to illustrate the grasp performance of a simple underactuated gripper to objects that are not centered in the grasp. The system consists of two fingers constrained to move only in linear translation. Each finger has both a return spring and a drive cable that exert force on the fingers. T_R and T_L represent the tension in the right and left drive tendons respectively. The main actuator tendon pulls on the system with force T_a. In this setup, the drive tendons are coupled to a single actuator using a floating pulley system. The floating pulley acts as a simple differential to match the tension force in each output tendon as shown in (1,2).

$$T_L + T_R = T_a \quad , \quad T_L = T_R \tag{1,2}$$

The floating pulley mechanism couples one actuator tendon to two output drive cables and the gripper is therefore underactuated. The floating pulley also permits the system to adapt to object offsets, u, within the grasp. Fig. 1b shows the finger displacements X_L and X_R as the actuator force increases, demonstrating this adaptability.

Assuming rigid contact with the object, any lateral motion of the object, u, would require a change in the finger position. Therefore, if we define L_R and L_L as the length of the drive tendon to the right and left fingers, we can say for this simple linear case that the change in length (dL_R) of the right drive tendon as a function of the change in object position is eq ual to one. The change in the length of the left drive tendon as a function of a change in object position is negative one.

$$\frac{dL_R}{du} = 1 \qquad \frac{dL_L}{du} = -1. \tag{3,4}$$

The floating pulley mechanism also requires that the average travel of the drive tendons is equal to the travel of the actuator tendon as shown in (5).

$$dL_L + dL_R = 2dL_a \tag{5}$$

The two-DOF prismatic system will be used as a simple example of an underactuated gripper in the following sections to describe the object acquisition and stability behavior of underactuated systems.

C. *Object Acquisition and Grasp Adaptability*

Grasp acquisition is the process by which a hand develops and builds contact forces with an object. In underactuated hands, the sequence of events that occurs during grasp acquisition determines the final hand configuration. Fig. 1a shows the three phases of grasp acquisition for the two-DOF prismatic gripper case. Phase 1 represents the period when the fingers are moving inward toward the object but have yet to make contact. Phase 2 describes the period of single point contact with the object in which only one contact point is established (F_R only) and is similar to pushing (as described in [7]). Phase 3 is the conclusion of the grasp acquisition when the final contact with the object is made and the grasp is complete (F_R and F_L are non-zero). One key aspect of underactuated grasping is the force developed by the first contact point during phase 2 of grasp acquisition. During this period, a non-closure grasp with the object is made and an unbalanced force is placed on the object. When grasping an object off a table, the friction force from the table surface may or may not be enough to overcome the unbalanced force provided by the single contact. Equation (6) shows the force balance of a grasped object. During phase 2 of grasp acquisition, i = 1 and the disturbance force vector $\vec{D}$, must offset any contact forces created by the gripper. For any non-zero offset of a symmetric object from the center of the gripper, $\vec{D}$ will remain non-zero in phase 3 as well, unless the object slips or is lifted. In (6), the force $\overrightarrow{F_{C_i}}$ represents all contact forces on the object.

$$\sum_{i=1}^{n} \overrightarrow{F_{C_i}} + \vec{D} = 0 \qquad (6)$$

The limits on $\vec{D}$ are a function of numerous parameters including mass, friction coefficient and even object size. [6]. Since the state of the object and contact conditions with the table are unknown, it is desirable to reduce this force as much as possible and will be quantified using the metric *P* defined in (7). For better adaptability, the value of *P* should be as small as possible.

$$P = Max(|\vec{D}|) \qquad (7)$$

For the simple two-DOF prismatic gripper shown in Fig.1, this parameter is a linear function of the spring constant, K, and the lateral positioning of the object (see point *P* in fig. 1c).

$$Max(|\vec{D}|) = K(X_L - X_R) \qquad (8)$$

D. Stability Behavior

In this paper, we will analyze the stability of an object in phase 2 of a grasp in terms of form closure. The traditional definition of form closure assumes rigid contact points [8] and therefore cannot be used for underactuated hands. We will adopt a similar definition of form closure used in [9,10] that defines it in terms of both kinematic (first order) and energetic (second order) stability.

Kinematic form closure rejects all motion of the object within the grasp. For example, in the prismatic case, eqns. (3,4) represent properties of the system relating to motion of the object u. Through (3,4,5) it can be shown that the change in length of the actuator tendon, dL_a with respect to object motion is zero:

$$\frac{dL_a}{du} = 0\,. \qquad (9)$$

It follows that even if the actuator tendon link was fixed, imposing the constraint that $dL_a = 0$, (9) would still hold. Fixing the actuator tendon length would therefore not restrict motion of the object u. If the conditions of object motion u violate any of the system constraints, the system would be said to be in kinematic form closure and would be able to resist motion of the object. For example, if both drive tendon lengths were fixed after the object was acquired, additional constraints

$$dL_L = 0 \quad and \quad dL_R = 0 \qquad (10,11)$$

are imposed. Since the properties of motion (3) and (4) violate constraints (10) and (11), the system would be able to prevent lateral motion u of the object and would be said to be in kinematic form closure.

Another measure of stability is energetic form closure (also referred to as Lyapunov stability). This metric considers changes in energy of the system with respect to a change in object position. A Lyapunov energy function V can be formulated that represents the total energy in the system. With regard to the two-DOF prismatic case, the energy of the system would result from changes in finger (and therefore spring) displacements. The relationship between the energy change of the system and motion of the object u is

$$For\ u = 0,\ \frac{dV}{du} > 0 \quad \text{else,} \quad \frac{dV}{du} < 0. \qquad (12)$$

When the object is centered, the spring energy must increase as a function of u. If there is an offset in the system the energy in the springs can decrease for some motions of the object. An object is said to be in energetic form closure if $\frac{dV}{du} > 0$, for all object motions, u.

With regard to analyzing the stability of friction based coupling systems presented in section IV, we will consider only the kinematic form closure measure of stability. [11] provides a full analysis of energy based stability arguments for underactuated hands.

III. Friction-Based Coupling Mechanism

The proposed friction-based coupling mechanism (FBCM) is based on the design of a floating pulley mechanism. However, instead of a free spinning pulley, this pulley is capable of opposing a torque produced by an unbalance in the output tendon forces.

The motion of the pulley is limited by a friction plate at the end of the pulley housing and a retention spring (see Fig. 2). Since the shaft of the pulley is free to slide within a slot in the housing, the normal force between the edge of the pulley and the friction plate is equal to the actuator force T_a, minus the force required to overcome the retention spring.

The torque on the pulley, τ_p from friction can therefore be described as

$$|\tau_p| \le (T_a - k_p \Delta s)\mu R_p \qquad (13)$$

where k_p is the retention spring constant, Δs is the travel of

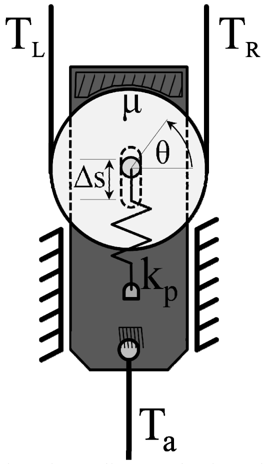


Fig 2. The friction based coupling mechanism alters the resistance to disturbances as a function of the actuator force, T_a. Here, μ represents the coefficient of friction between the edge of the pulley and the friction plate, Δs represents the full travel of the retention spring, θ is the rotation of the pulley, and k_p represents the retention spring constant. Note: the tendon does not slip on the pulley

the pulley before contact is made with the friction plate, μ is the coefficient of friction between the pulley and the friction plate, and R_p is the radius of the pulley.

When this coupling mechanism is used in place of the standard floating pulley with a fixed actuator tendon, the constraints of the system become

$$dL_a = 0 \quad \text{and} \tag{14}$$

$$d\theta = 0 \quad dL_R = 0 \quad dL_L = 0 \tag{15,16,17}$$

as long as the inequality expressed in (13) is valid. Where L_R and L_L are the length of the right and left drive cables and θ is the rotation angle of the pulley. For the prismatic system in fig. 1a, the addition of constraints (15, 16, 17), will make the system achieve kinematic form closure if (13) holds. One can easily translate the effects of external disturbance forces $\vec{B}$ on the object to the torque on the FBCM pulley used in (13). It is assumed that $\vec{B}$, is a lateral force on the object. Fig 3 shows the ability of the system to remain in kinematic form closure as a function of the actuator force T_a with varying parameters of $k_p\Delta s$ and μ. With a positive value of $k_p\Delta s$, the rejection of disturbance forces does not occur until this value is overcome.

In order for the FBCM to adapt to object offsets, the coupling pulley must rotate to change the relative displacements of the right and left tendons. Therefore, the max force to keep the object in position with the new coupling mechanism in phase 2 is

$$Max(|\vec{D}|) = K(X_L - X_R) + (T_a - k_p\Delta s)\mu \tag{18}$$

where the first term is identical to the floating pulley case while the second term is the additional force to overcome the torque in the FBCM. In order to not increase the adaptability

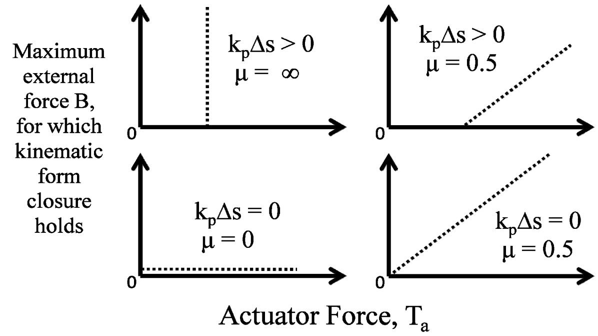


Fig 3. Chart showing how parameters $k_p\Delta s$ and μ affect the ability of the system to maintain kinematic form closure.

metric *P*, the torque required to rotate the pulley during phase 1 and phase 2 should be zero, meaning the friction in the FBCM should ideally not engage until phase 3.

IV. Parameters for Friction-based Coupling Mechanisms

In practice, most underactuated hands use revolute joints as opposed to prismatic joints like those presented in fig 1a. For this reason, the ideal design parameters of a FBCM will be found for a two-DOF revolute gripper (shown in Fig. 4. and Fig. 6). The design parameters will minimize the adaptability metric *P*, ensure the system can reject external disturbances $\vec{B}$, and allow for motion of the object for extreme values of $\vec{B}$ as a safety mechanism.

The form of (18) allows us to write a similar equation for the revolute case. Here, a_R represents the contact moment arm of F_R (Fig. 5), K is the spring constant of the base joints and R represents the tendon radius about the base joint.

$$Max(|\vec{D}|) = \frac{K}{a_R}(X_L - X_R) + \frac{R}{a_R}(T_a - k_p\Delta s)\mu. \tag{19}$$

The second term of (19) is zero when the retention spring force, $k_p\Delta s$, is equal to the actuator force T_a. The maximum force that is required by the actuator while still in phase 2 of grasp acquisition is equal to the force required at full travel of the fingers. If the size of the object is unknown, we must assume that the retention spring must resist the force required to move the fingers through their full range of travel (in order to fully close). Thus,

$$k_p\Delta s = \frac{K}{R} * \max(X_L + X_R) \tag{20}$$

If the size of the object is known, then the sum of X_L and X_R and can be used in (20) to engage the friction coupling at the exact start of phase 3.

The friction coefficient μ can be chosen based on the relationship between actuator force and disturbance force on the object. In the prismatic case, the contact point locations were known to exist along the same axis of travel as the fingers. The revolute gripper however, does not have the same restriction for contact locations. As seen in Fig 5. The

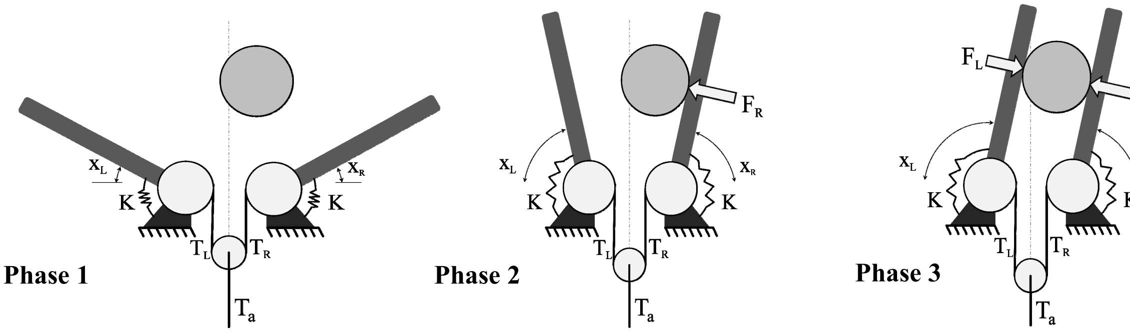
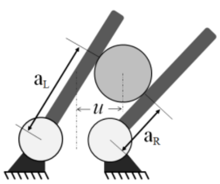


Fig 4. Phases of grasp acquisition in a two DOF revolute gripper. Shown here with simple floating pulley coupling mechanisms.

moment arm of contact between the right finger and the object, a_R, can be different than the moment arm of contact between the object and the left finger, a_L. The effect causes the unbalanced contact force $\vec{D}$ to increase linearly as a function of the actuator force in phase 3 of the grasp. The minimum friction coefficient μ to negate these effects is shown in (21). With current grippers, the centering force on the object will increase as the actuator force increases.



$$\mu > \frac{(a_L - a_R)}{(a_L + a_R)} \tag{21}$$

Fig 5. Offset Configuration

The difference in moment arms of the contact points is a function of the object size and the position offset, u, within the grasp span. Therefore, μ must be chosen for the greatest expected object offset within the grasp.

Fig. 7 shows the region of kinematic form closure for the revolute case with parameters described in Table I. The parameters were chosen based on (19), (20) and (21). Points G, H and I, represent the initiation of the three phases of grasp acquisition. The path from G to H represents the closing of the gripper around the object. At point H, the right finger begins to exert forces on the object. If the system was designed appropriately, point I will correspond to phase three of grasp acquisition and the initiation of friction forces within the coupling mechanism. The value of the contour at location I (0.85 N), also represents the adaptability metric P, since this is the maximum disturbance force placed on the object before closure occurs. With an actuator force of 60 N at point J, the system is able to remain in kinematic form closure if the object is subjected to an external load between -4.3 and 9.2 N. The asymmetry is due to the effects of (21) where $a_R \neq a_L$. For this example, a friction coefficient of 0.8 was shown. One can easily see that increasing the friction coefficient would expand the stable region.

V. Implementation

A prototype friction based coupling mechanism was developed featuring a toothed interface between the rotating

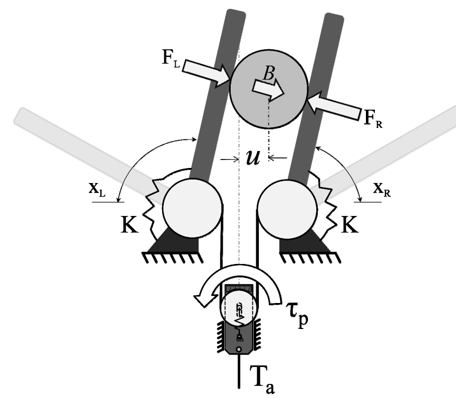


Fig 6.Revolute two-DOF gripper with friction based coupling mechanism. Here the additional parameters of coupling pulley torque τ_P and external disturbance force B are shown.

pulley and the friction plate (μ= large), as shown in Fig. 8. The retention spring allows for free rotation of the pulley up to a total actuator force of 45 N. A total actuator force of 50 N was required to overcome the joint springs in the fingers at the fully closed position. At an actuator force of 55 N, the engagement of the toothed interface allows the output tendon tensions to vary by the total force of the actuator (F_R = 0, F_L = 55 N). The system was tested using a set of two-link fingers, see Fig. 8, with internal coupling similar to the Hirose fingers as described in [1]. The friction based coupling mechanism stabilized the object laterally within the grasp but as expected, did not substantially prevent object motion perpendicular to the position measurement u. The kinematics of the fingers allowed for internal changes of the proximal and distal link position to occur without requiring motion in the tendon [5].

VI. Discussion

The friction based coupling mechanism presented in this paper offers greater grasp stability over previous underactuated coupling mechanisms. This is achieved by scaling the resistance to lateral motion as a function of actuator force. When high adaptability is needed during phase 1 and 2, the actuator force is low, while in phase 3, when the adaptability should be rejected, the actuator force is much higher. For standard underactuated coupling mechanisms, the relationship described in (5) is independent of actuator force and thus the rejection of external disturbances does not change with grasp force. For standard

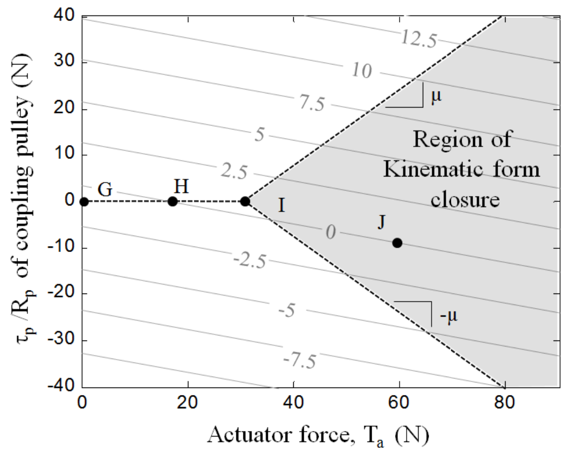


Fig 7. Kinematic form closure region for a revolute two-DOF gripper with friction based coupling mechanism. The contours represent the disturbance force $\vec{B}$ in newtons. Properties of the gripper are shown in table 1.

floating pulley systems you can never achieve kinematic form closure due to the residual adaptability. FBCMs enable that closure to be achieved with little negative impact to grasp acquisition performance.

The adaptability behavior of FBCMs can be tuned due to the introduction of a retention spring in the mechanism (see Fig. 2) that lets the user tune the system so that the increase in resistance to lateral motion starts near the starting point of phase 3 (shown in (20)). Furthermore, since the actuator force is a controlled parameter of the system, object stability can be altered mid-grasp by changing the object grip force. A common practice in underactuated hands is to incorporate non-backdrivable mechanisms (NBDMs) into the actuation coupling that prevent forces on the links needing to be balanced by the actuator. Most lead screws and worm gear systems, common to NBDMs, are ~40% efficient [13]. The addition of two NBDMs to the two-DOF prismatic case in Fig. 1a, would prevent reverse motion of the drive tendons and impose constraints (10) and (11) on the system. While the addition of (10) and (11) to the system create a kinematic form closure condition that could reject external disturbances, the use of NBDMs reduces the efficiency of the system and even increases the value of the adaptability metric *P*. NBDMs also do not provide any force overload condition to extreme external forces. If the friction coefficient, μ, was set to be very large (through a toothed mesh, for instance), the system would act the same as with two NBDMs once phase 3 of the grasp is reached.

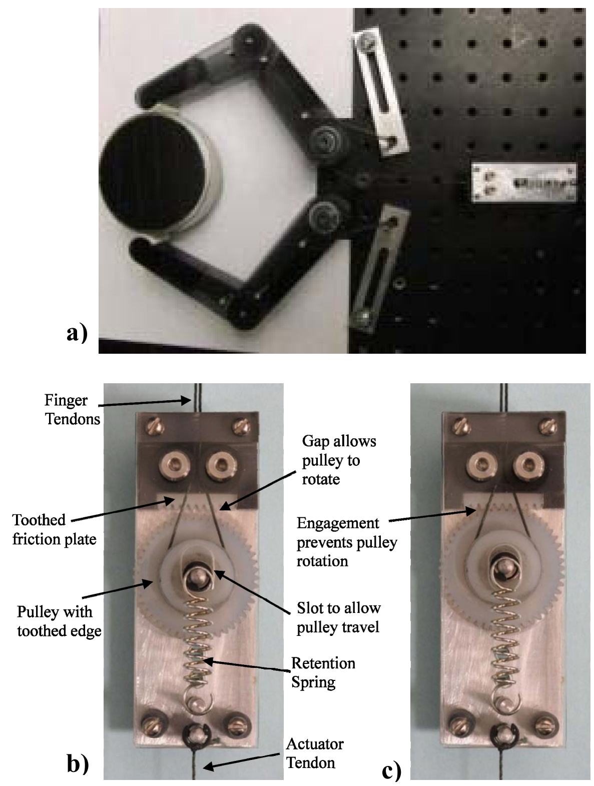


Fig 8. A prototype friction based coupling mechanism with toothed interface between pulley and friction plate is used to actuate a simple gripping system. a) shows the gripper system being actuated through a friction based coupling mechanism. The system can allow the coupling pulley to freely rotate, as shown in b), or lock in position as shown in c).

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