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Design of Hands for Aerial Manipulation: Actuator Number and Routing for Grasping and Perching

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Abstract— **This paper examines aspects of robot hand performance specific to grasping and perching from an aerial vehicle and shows how various hand design parameters affect performance. Specifically, we consider hand performance when subject to external forces imparted to the hand from carrying a payload or from perching on a fixed item and explore the impact of design and grasp parameters including tendon routing/pulley ratio, object size, and palm size on the performance of both fully and underactuated designs. Our results show that underactuated designs utilizing a single actuator per finger are sufficient in all cases we studied, but that fully actuated designs can perform better for perching applications. Additionally, we find that increasing the palm width improves performance both when perching and grasping, and that a small distal/proximal pulley ratio is beneficial for payload carriage but counterproductive for perching.**

I. Introduction

As aerial vehicles begin to take on increasingly greater roles in both civilian and military applications, physically interacting with the world through aerial manipulation is becoming possible. However, the challenges associated with grasping and manipulation from aerial vehicles are many: necessity for lightweight structures, prompting simplistic and efficient designs; low impedance and instability of the vehicle during flight, requiring and allowing relatively small contact force magnitudes and in only a few directions; and limited ability to orient an end-effector with respect to the vehicle, among others. The design of the hand for an aerial manipulator must take into account these challenges and limitations in order to allow for good performance. In this paper we discuss how the choice of the number of actuators, the routing of those to the links of a hand, and other factors such as palm width affect the ability of the hand to perform both payload carriage and perching tasks.

While aerial manipulation platforms are becoming more prevalent, there have been few concerted efforts to investigate designs of grippers for these systems. Instead, most vehicles are equipped with simple manipulators or repurposed hands based on existing designs [1-9]. Many of these systems have utilized underactuated hand designs because the benefits of underactuation, including adaptability, robustness, and lower hand complexity and mass. Although beneficial during all kinds of manipulation

Figure 1. Example of a UAV grasping and carrying an object using an underactuated hand [10].

tasks, these advantages are especially useful when attempting to perform grasping tasks from a dynamic vehicle such as a quadrotor or helicopter where the system mass and control simplicity are critical. These systems have then been used to demonstrate basic grasping or perching tasks capabilities.

In all of these cases, existing hand designs have been slightly modified to integrate with the desired vehicle but the basic parameters that affect their grasp performance have not been optimized for this application. For example, Mellinger et al. attached a simple single degree of freedom claw to a quadrotor and demonstrated it grasping rectangular blocks that can be assembled into structures [6]. Pounds and Dollar mounted a modified version of the SDM Hand to a radio controlled helicopter and used this system to demonstrate grasping of objects from hover as shown in Figure 1 [1]. Doyle et al. present the design for a passive perching mechanism attached to a quadrotor that actuates a hand directly derived from the SDM hand and performed basic tests of the overall system's stability in response to disturbances [2]. Thomas et al. utilize a linkage based hand derived from the SDM hand and Festo EXOHand mounted to a single DOF arm to perform grasps at high speed [3]. Although all of these grasper and vehicle systems have shown some degree of utility, none were specifically designed or optimized for the expected loads that grasping and perching imparts on them. Instead, the design of the SDM hand, on which most of these manipulators were based, focused on grasping tasks performed from a robotic manipulator and optimized the hand for error tolerance and grasp stability, not the ability to resist disturbance forces [11].

In this paper, we simulate the behavior of a representative hand based upon the SDM hand in response to the forces imparted by carrying and perching tasks shown in Figure 3. We discuss the impact of various design parameters on the hand's performance, measured in terms of the summed total tendon tension normalized by the magnitude of the

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disturbance, in response to the expected loads during perching and carrying tasks and compare the performance of underactuated and fully actuated designs. We begin by presenting our grasp model. We then discuss how the configuration of the object and joints is defined and how, based on this configuration, the contact and tendon forces may be calculated. Next, we present results showing the impact of various design and grasp parameters including pulley ratio, palm width, and object diameter on the tendon tension required to counteract various disturbance forces. Lastly we show the impact of these design parameters on a hand design and how they can be selected to minimize total tendon tension and indirectly actuator size in the hand. From this we conclude that although the performance of an underactuated hand is worse under some conditions, it is sufficient and because it halves the number of actuators needed, may reduce the overall weight of the hand.

II. Methods

Using a model to predict the performance of a grasping hand or foot is a notoriously difficult problem. The huge diversity of objects, initial object poses, and possible hand grasping poses make it impossible to exhaustively model a hand's behavior. Because of this tractability problem, we are restricted to prototypical cases, or object-agnostic proxies for performance such as the enclosed volume of a pre-grasp pose. In this paper, we desire to have a model for understanding holistic hand behavior under various grasping conditions in relation to important design considerations, in particular the maximum actuator force required to hold an object in equilibrium when subject to various disturbance forces. We measure this performance in terms of an input-output efficiency between the magnitude of the applied disturbance force and the summed total tendon tensions required to oppose it.

Therefore we have developed a model of a two digit hand that relies on a number of common simplifying assumptions. This model allows us to systematically define a grasp pose and based on this pose calculate the minimum tendon tension that keeps the object and digits in equilibrium for an applied disturbance force. We first define the grasp pose and contact points by maximizing the wrap of the digits about the object. We then calculate the minimal tendon forces required to counteract an applied disturbance by performing a constrained minimization of the contact energy. Lastly, we evaluate the quality of a design based upon a number of factors including the existence of a solution and if it exists, the ratio of the required actuation force to the disturbance force. The performance of the hand with regard to this ratio is particularly important for aerial vehicles where the payload of the vehicle is limited, emphasizing the need to minimize the number and size of the actuators used in a hand.

A. *Model assumptions*

In this paper, we consider a 2D planar hand composed of two symmetrical digits separated by a palm similar to the SDM hand[11]. Each digit may be fully actuated by a pair of tendons or may be actuated by a single distally inserted tendon as shown in Figure 3. For this hand we vary the size of the object, the width of the palm, and the ratio of the proximal to distal tendon moment arms. We also consider both the fully actuated and underactuated tendon configurations.

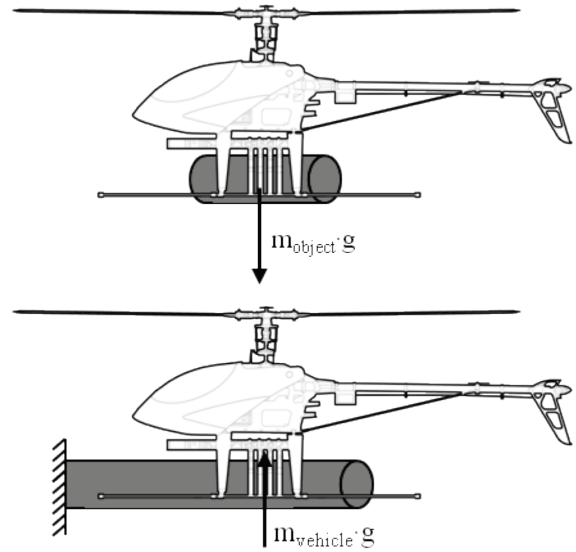

Figure 2. Diagram showing a helicopter carrying an object (top) and perching (bottom). When carrying the object, the hand has to resist a downward force to the object to oppose the objects mass. In contrast, when perching, the hand has to transmit an upward force from the perch to the vehicle.

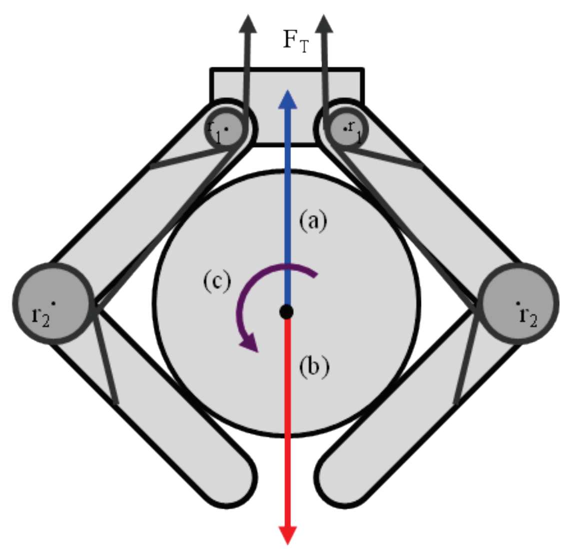

Figure 3. Diagram of hand showing proximal and distal tendons and example of upward or palmar disturbance force (a), downward disturbance (b), and moment disturbance (c).

B. *Grasp Pose*

The joint angles, object position, and contact locations, or grasp pose, are determined for any object diameter and set of hand parameters as follows. First, we assume that the object can be approximated by a circle and that each link is tangent to the object while grasping as is often the case in grasp analysis [12]. We then find the object position relative to the hand that maximizes the angular wrap of the digits about the center of the object as measured from distal contact on one digit to distal contact on the other as shown in Figure 4. The contacts between the object and hand are assumed to be at the tangency points.

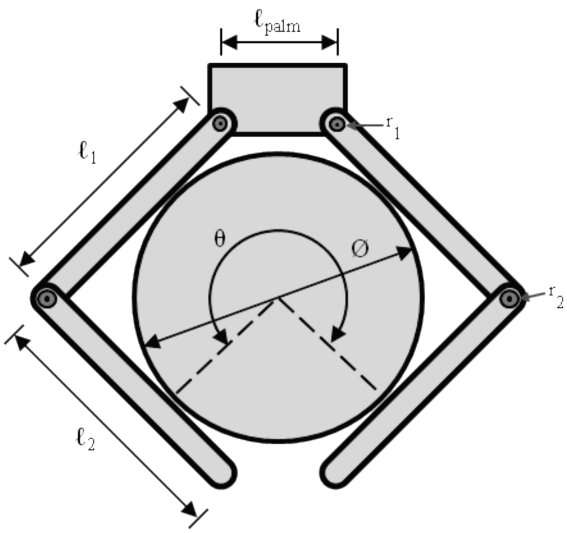

Figure 4. Example of manipulator wrapped about a circular object. Hand and object parameters including wrap angle, θ, object diameter, ⌀, proximal link length ℓ_1, distal link length ℓ_2, palm length ℓ_{palm}, proximal pulley radius r_1 and distal pulley radius r_2 are shown.

C. Force Modeling

Based upon the assumed grasp pose and contact locations, a relationship between a force applied to the object and the tendon forces needed to oppose it can be found. However, because the contacts between links and object over-determine the kinematics of the grasp (4 link and 3 object DOF = 7 possible digit and object motions, 5 contact points x 2 (normal + shear) = 10 constraints), infinitely many possible solutions exist, making it impossible to solve for the contact forces directly. Instead, we propose that the most likely solution is one that minimizes contact and tendon forces and find a valid solution that meets this criterion. We can do this by assuming some small, equal contact compliance at each point in normal and shear directions [13]. The energy of contact and actuation is then minimized at equilibrium, leading to a least squares minimization of contact forces and linear minimization of actuation forces. This can be solved as a quadratic program of multiple variables corresponding to the individual shear and normal forces as well as the tendon forces subject to equality and inequality constraints. The quadratic program can be represented as follows:

$$f(x) = \frac{1}{2}x^T H x + f^T \quad (1)$$

Where

$$x = [s_1, n_1, s_2, n_2, s_3, n_3, s_4, n_4, s_5, n_5, T_1, T_2, T_3, T_4]^T \quad (2)$$

$$H = \begin{bmatrix} I_{10} & 0_{10,4} \\ 0_{4,10} & 0_{4,4} \end{bmatrix} \quad (3)$$

$$f = \begin{bmatrix} 0_{1,10} \; 1 \; 1 \; 1 \; 1 \end{bmatrix}^T \quad (4)$$

The vector x is composed of the shear and normal components of each contact force and the four tendon tensions. The coefficients H and f of the quadratic function correspond to squaring both the shear and normal components of each contact force (s_n n_n) and linearly weighting the tendon forces (T_n) respectively.

This minimization is constrained by the friction cones and directionality of the normal forces, and by the balance of forces on the joints (torques due to tendons = torques due to contact forces). The inequality constraint on each shear force and normal force can be expressed as $|F_s| - \mu F_n \leq 0$ and $-F_n \leq 0$ respectively. The relationship between the tendon and contact forces can be expressed as an equality constraint in terms of the Jacobian and Transmission matrices as follows[14]:

$$[J^T \quad T^T]x = [F_x \quad F_y \quad \tau \quad 0_{1,4}]^T \quad (5)$$

Here, the Jacobian J relates the disturbance forces to the contact forces and contact forces to joint torques and the transmission matrix (T) relates the tendon forces to joint torques. This constraint ensure that the grasp is in static equilibrium and that the tendon and contact forces are related based upon the assumed hand geometry. The quadratic program and associated constraints are implemented in MATLAB and solved using the quadprog function. This minimization will yield a plausible set of contact and actuator forces for an arbitrary disturbance applied to the object. The underactuated case may be analyzed in the same manner by repeating the optimization with the additional constraint that the proximal tendon forces equals zero.

D. Grasp Evaluation

We apply this model to a range of possible hand configurations and disturbances. Specifically, we analyze the performance of a hand in response to a downward force representative of the mass of the object it is carrying and an upward force and moment corresponding to mass of the vehicle and torque due to the center of mass not being directly above the hand that the hand must support while perching. For each of these cases, we vary the object size, pulley ratio (distal pulley radius/proximal pulley radius), and palm width. We also consider both the fully actuated and underactuated case for each configuration.

For each parameter set we first determine if valid fully and underactuated solutions exist and, if a solution exists, compute the sum of normalized tendon tensions that are required to counteract the disturbance. Based upon these two parameters we can then evaluate if the particular hand configuration is capable of maintaining the grasp and opposing the disturbance force and if so, how efficiently it does so. Efficiency, measured as the ratio of the tendon tension divided by the disturbance force corresponds to the actuator power the hand would require, something we wish to minimize on aerial vehicles. Particular configurations are judged based upon the range of conditions under which they can maintain the grasp and how efficiently they do so.

In this paper the response of four example hand parameter sets to upward and downward disturbance forces were evaluated. Basic hand geometry was based upon the SDM hand: proximal and distal link lengths were equal[11]. However, for simplicity, all dimensions of the hand and object were normalized by the total digit span (length of digit 1 + length of digit 2 = 1). Pulley ratios (proximal / distal moment arm) were varied between 0.55 and 1 based upon past simulations of under actuated hands [13]. Palm width was varied between 0 and 0.15 and object diameter ranged between 0.01 and 0.5 relative to the unit hand span.

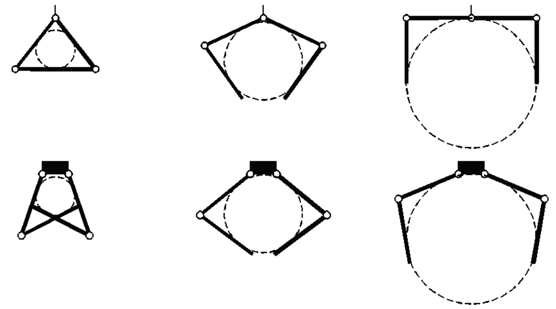

Figure 5. Examples of grasps for various object diameters and palm widths. Since all lengths have been normalized by the total length of the two digits, the object diameter and palm width are expressed relative to this length and are unitless, The left column shows 0.1 diameter objects, the middle 0.3, and the right 0.5. The first row shows hands with a palm width of zero while the second row shows hands with a palm width of 0.1

Examples of grasps of 0.1, 0.3, and 0.5 diameter objects and hands with palm width of 0 and 0.1 are shown in Figure 5. Lastly, a coefficient of friction of 0.5 was assumed based upon previous work that showed that coefficients of friction between 0.2 and 0.7 are observed when dealing with common objects [17].

III. Results And Discussion

Figure 6 and Figure 7 show how the performance of various hand designs varies as a function of object diameter in response to a disturbance force or moment representative of either grasping or perching. Each subplot shows the performance of four different hand designs in response to a particular disturbance where either the pulley ratio or palm width is varied. For each design, its fully actuated performance is plotted using a solid black line while its underactuated performance (where valid) is plotted using a dashed grey line. As these figures demonstrate, the pulley ratio and palm width have significant effects on the performance of the hand in response to a disturbance.

A. Pulley Ratio

Figure 6 shows the performance of the hand designs with a palm width of 0 as we vary the pulley ratio from 0.55 to 1. When subject to a downward disturbance, Figure 6 (a), representative of grasping and carrying an object, all four designs exhibit an increase in required tendon tension in response to increased object size. Designs with a larger pulley ratio require greater tendon force for equivalent sized objects. This trend is true for both under and fully actuated hands and the results for both are identical. Under these conditions our model shows that an underactuated hand design performs just as well as a fully actuated one and that a small pulley ratio is desirable in a hand.

Figure 6 (b) shows the performance of the designs in response to an upward disturbance force, equivalent to balancing on a perch. Under these conditions, valid grasps exist for all object diameters. Tendon force approaches zero for objects of both zero diameter and large objects whose diameter equals half the hand span. This is because objects of these diameters will contact the palm, as can be seen in Figure 4, and when the object contacts the palm, upward forces are directly exerted against the palm instead of the fingers, and no tendon tension is required.

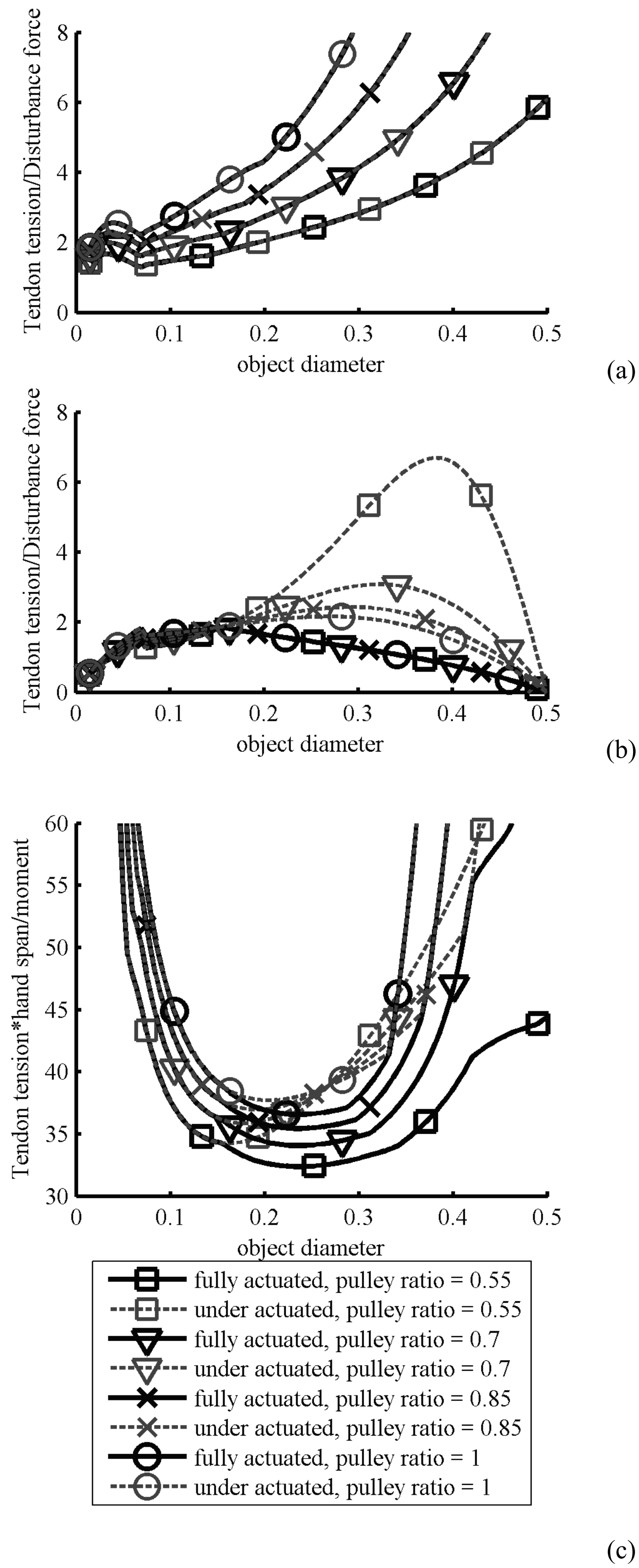

Figure 6. Total tendon tension normalized by the magnitude of the disturbance force as a function of object diameter required to resist a downward disturbance representative of grasping (top) and an upward disturbance (middle) and moment disturbance (bottom) representative of perching, when $\mu = 0.5$ and the palm width = 0. Performance of each design when fully actuated is shown with a solid line and underactuated with a dashed line.

For intermediate object sizes, fully actuated designs with different pulley ratios perform identically. This is because the upward disturbance can be opposed completely by contact forces exerted by the proximal links. Therefore, the fully actuated designs rely exclusively on the proximally inserted tendons in this case to oppose the force and the tension does not change.

In contrast, the underactuated configurations require significantly greater tendon force than the equivalent fully actuated configuration and their performance is directly impacted by the pulley ratio. In this case, a larger pulley ratio improves performance of the underactuated hands for intermediate sized objects. This is because the distally inserted tendons of the underactuated hand produces contact forces on both the proximal and distal links. Therefore, greater overall tendon tension is required to produce sufficient proximal contact forces to oppose both the disturbance force and distal contact forces. Furthermore, because the pulley ratio directly corresponds to the torque exerted about each joint, a higher pulley ratio equates to a larger torque about the distal joint. This torque in turn corresponds to larger distal contact forces that must be reacted on the proximal links.

Figure 6 (c) shows the performance of the designs as a function of object diameter in response to a disturbance moment. Under this condition object diameter has a similar effect on all four designs: in all cases, hands require significantly higher tendon tension for objects smaller than 0.1 and larger than 0.3. Pulley ratio also has a direct effect on the hands performance. Reducing the pulley ratio improves the performance of fully actuated hands for all object diameters and underactuated hands for small objects when subject to a disturbance moment. However for larger objects, increasing the pulley ratio improves the performance of these underactuated designs. Lastly, below diameters of about 0.15, the performance of underactuated and fully actuated hands is equivalent. However above this diameter, underactuated designs perform worse, requiring more tendon tension than their fully actuated counterparts.

B. Palm width

Figure 7 show how the performance of various potential hand designs varies as a function of object diameter in response to a disturbance force or moment for various palm widths. Each of these designs has a pulley ratio of 0.7 and the palm width ranges from 0 to 0.15. The fully actuated performance of each design is plotted using a solid black line while the underactuated performance (where valid) is plotted using a dashed grey line. In general, a larger palm improves the performance of these designs in response to a disturbance. These results show that when designing a hand to minimize the tendon tension required to oppose an upward, downward, and moment disturbance, a larger palm will improve the hands performance in almost all cases. However as can be seen in Figure 7 (a), the impact of palm width is minimal for a downward disturbance. In this situation, a wider palm increases the wrap about the object, thereby improving the grasp. However because the largest palm width is still small in comparison to the length of the fingers it does not have a substantial effect.

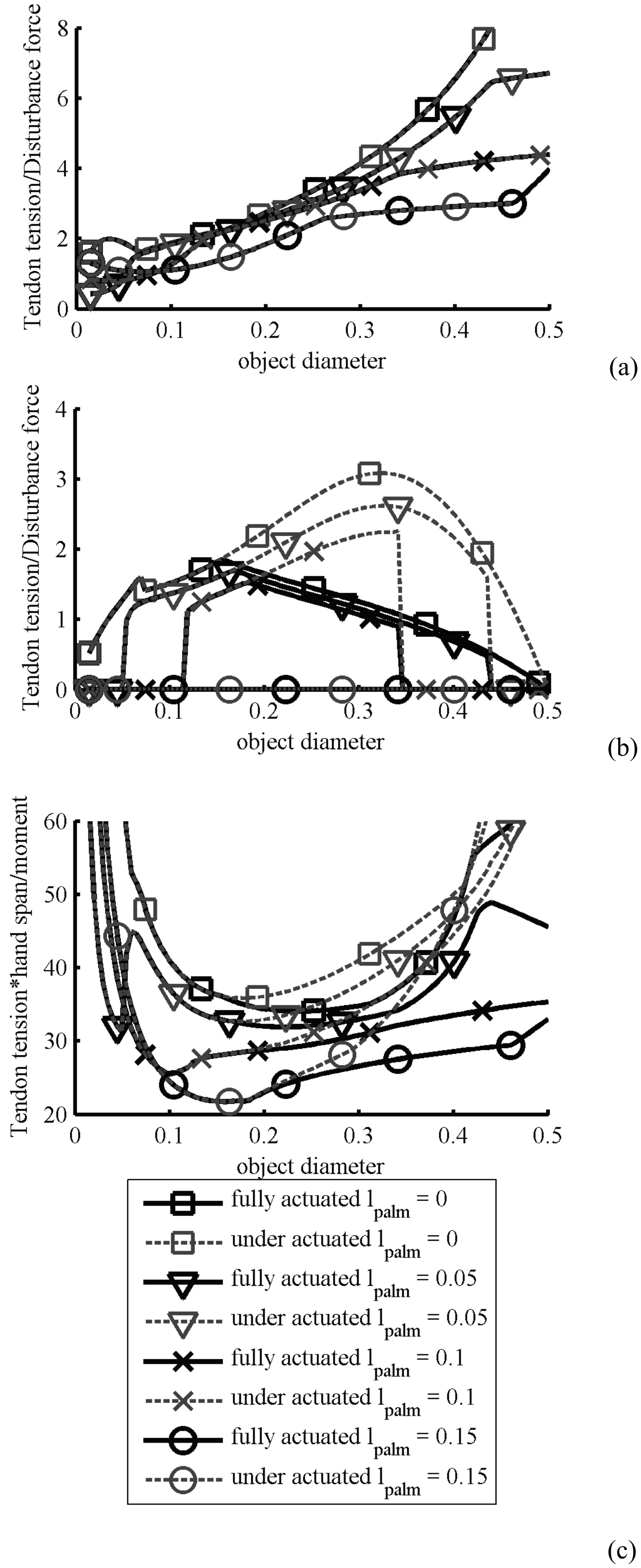

Figure 7. Total tendon tension normalized by the magnitude of the disturbance force as a function of object diameter required to resist a downward disturbance representative of grasping (top) and an upward disturbance (middle) and moment disturbance (bottom) representative of perching, when the pulley ratio = 0.7 and the coefficient of friction = 0.5. The impact of palm spacing is shown in this figure: increasing the palm spacing reduces the required tendon tension regardless of disturbance direction.

Figure 7 (b) shows the behavior of the designs in response to an upward disturbance. Under these conditions, the tendon force equals zero for object diameters of 0 and 0.5 for all of the designs. However for intermediate sized objects, palm width and degree of actuation have significant effects. First, increasing palm width decreases the range of diameters where tendon force is required to oppose the disturbance until no force is required for any object diameter as can be seen when palm width equals 0.15. This is because small and large objects directly contact the palm from within a grasp and the disturbance force is transmitted directly into the palm. Furthermore, increasing palm width increases the range of object diameters where the object contacts the palm and actuation is not necessary to oppose the disturbance. This trend continues until no actuator force is required for any diameter as is the case for a hand with a 0.15 wide palm.

Second, for the object diameters where the object does not contact the palm, increasing palm width reduces the required tendon tension required for both fully- and under-actuated hands for a given object diameter. In both cases, a wider palm reduces the tendon tension by allowing the proximal digits to wrap further around the object and thereby react more of the disturbance force through the shear component of the contact force. Lastly, underactuated hands perform significantly worse than their fully actuated counterparts over a range of intermediate object diameters. For larger objects, underactuated designs require up to twice as much tendon force as fully actuated hands.

Figure 7 (c) shows the effect of palm width on the performance of the designs when subject to a moment disturbance. In general, all of these designs perform poorly for small objects (less than 0.1 in diameter) and performance also degrades for larger objects (greater than 0.35 in diameter). Performance of under and fully actuated designs is identical for objects of less that about 0.15 and above this diameter, underactuated designs perform worse than their fully actuated counterpart. Furthermore, a larger palm results in better performance of the fully actuated designs and improves performance of underactuated designs except when grasping large diameter objects.

C. *Design Conclusions*

First, our model and simple intuition suggests that, based upon our desire to minimize the required tendon tension we should first maximize the radius of both the proximal and distal pulley, thereby maximizing the tendon moment arm. However this ignores the fact that pulley radius is fundamentally limited by the packaging constraints of the hand: above a certain diameter the pulleys will protrude too far from the links and interfere with the grasp. It also does not take into account that increasing the pulley radius also increases the tendon excursion for the same design. Therefore we do not consider pulley diameter directly in our optimization.

Instead we investigate the impact the ratio of radius of the proximal to distal pulleys. Based upon the contradictory trends for grasping and perching, we cannot directly optimize the pulley ratio of an underactuated hand that will be used for both grasping and perching tasks. Instead, conflicting trends for the influence of pulley ratio on the behavior of hands in response to upward and downward disturbances suggest that an intermediate value that exhibits acceptable performance under both conditions should be used.

Secondly, we investigated the effect of the distance between the proximal joints or palm width on the hand's performance. The results show that under most conditions, increasing the palm width will improve a hand's performance until a valid grasp can't be found. However there are aspects of palm width that this model does not consider such as the benefit of coaxial proximal joints.

Therefore when interpreting the results of this model and applying them to a hand design, it is important to consider additional features that may balance the hand's performance in both tasks. For example if we consider the addition of extension hard stops to the proximal joints, when perching, the proximal joints may be forced against the hard stop, reducing the need for tendon actuation in that instance. Therefore with hard stops, the pulley ratio could be optimized more for grasping tasks. Similarly, since the proximal links serve the same function as the palm when they are against the hard stop, palm size may be reduced without compromising the perching performance.

To summarize, these results show that an underactuated hand is sufficient to perform both grasping and perching tasks. However, we show that in comparison to fully actuated hands, an underactuated hand will performance worse when subject to a moment or upward disturbance. These results also suggest that a good hand design for both grasping and perching tasks will have an average pulley ratio and large palm, both of which should result in a hand with good performance to all three kinds of disturbances. However we also suggest that additional features not included in our model such as joint hard stops may further improve the performance of a hand if intelligently included by a designer.

IV. Limitation and Future Work

This model suffers from a number of limitations. Based upon our assumptions, the object and contact locations are fixed for each grasp, preventing reconfiguration in response to the disturbance forces. In a real hand an object may slip and the links may reconfigure slightly in response to a disturbance force. This reconfiguration in turn alters the relationship between the disturbance force and tendons, potentially improving or harming the performance of the hand. Instead, our model assumes that the grasp can't reconfigures and instead finds a solution that keeps the system in equilibrium in its current pose.

Another limitation of this analysis is that we only consider three specific disturbances when in reality, a hand would experience simultaneous disturbance forces and moments acting in many different directions and relative magnitudes depending on the task. Although the three disturbances we investigated in this work represent the primary disturbances we expect to see, in the future we will consider the hand's performance when subjected to disturbances in all possible directions and combinations of disturbance forces and moments.

Additionally, this model only considers a hands ability to maintain a grasp in response to a disturbance. It does not consider other aspects of hand performance such as grasp acquisition robustness or the hands transmission of disturbances to the vehicle, both of which are also important for aerial manipulation and relate to the parameters we explored. For example, our results suggest that a wider palm will improve the performance of a hand but increasing the palm spacing will reduce the torsional compliance of the hand about its proximal joints, reducing its ability to reject disturbance moments applied to the body of the vehicle through the hand.

V. Conclusion

In this paper we analyze the performance of tendon based graspers under loads representative of aerial manipulation-based grasping and perching tasks. The results indicate that while the performance of underactuated and fully actuated hands in response to a downward disturbance is nearly identical, the performance of underactuated designs in response to upward forces and moments (that would be applied during perching) is substantially worse. Similarly, it shows that for a fully actuated hand, increased palm width improves performance both while grasping and perching, but that increasing pulley ratio only improves performance while grasping. For an underactuated hand, an increased palm width and decreased pulley ratio improves performance while perching, and a larger pulley ratio improves performance while grasping. Although this model does not fully capture all relevant aspects of hand design for grasping from aerial vehicles, it demonstrates that two link underactuated hands are capable of performing both types of tasks with only modest decreases in performance in comparison to an equivalent fully actuated design. While this may seem to suggest that fully actuated hands should be used for aerial grasping and perching tasks, the decrease in performance may be offset by the decrease in the total number of actuators used in an underactuated hand.

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