Novel Differential Mechanism Enabling Two DOF from a Single Actuator: Application to a Prosthetic Hand

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***Abstract*— There will always be a drive to reduce the complexity, weight, and cost of mobile platforms while increasing their inherent capabilities. This paper presents a novel method of increasing the range of achievable grasp configurations of a mechatronic hand controlled by a single actuator. By utilizing the entire actuator space, the hand is able to perform four grasp types (lateral, precision, precision/power, and power) with a single input resulting in a potentially lighter and simpler hand design. We demonstrate this strategy in a prototype hand that is evaluated to determine the benefit of this method over the addition of a second actuator. Results show a decrease in weight but a 0.8 sec transition time between grasp types with the proposed method. The prototype hand can be controlled by a single EMG signal that can command a change in grasp type or an opening/closing of the hand. We discuss the potential of this mechanism to improve prosthetic hand design as compared to current myoelectric systems.**

I. INTRODUCTION

WITH the development of highly articulated robot hands, there is a fundamental problem associated with the packaging and control of numerous actuators to perform a wide range of functions. Specifically in the field of robotics and prosthetics, there is a tradeoff between the number of independent motions and the weight and complexity of the entire device. Even if the device is able to control 22 independent degrees of freedom (DOF), as is the case for human hand motion, the packaging of such a system would be too large and heavy for practical use. Within the field of prosthetic hand design, the weight of the device remains one of the most distinguishing factors that limit adoption by amputee users. A survey of myoelectric prosthesis users found that users rated the weight of the device as a 70 on a scale of 0 (not important) to 100 (most important) with regards to the design priorities of prosthetic hands [1]. One key means of reducing the weight of the device is to reduce the number of actuators used within the hand. DC motors and their associated transmission mechanisms make up a large amount of the total weight of highly dexterous robotic hands.

A study of hand motion [2,3] has shown that most common activities can be achieved with a finite set of hand grasping motions. Therefore, hand designers should evaluate the tradeoff between additional hand functions with the added weight and packaging constraints of additional actuators. This tradeoff has led to the study of the principle components of grasping in which each additional actuator controls a linear subset of all DOF and thus best utilizes the benefit of additional actuators. A practical implementation of the grasp principle components was developed in [4].

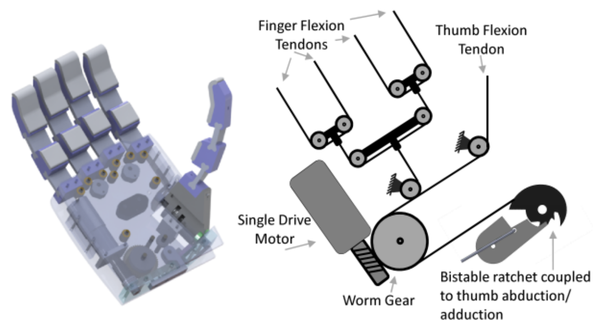

Fig. 1. The prototype hand utilizes a single motor to open/close the hand as well as switch grasp types to perform lateral, precision, and power grasps.

One observation of the major differences in the grasp types used for acquisition and holding of typical objects is the positioning of the thumb prior to making the closing motion of the hand [2] and the timing of when the fingers are closed in relation to the movement of the thumb. The i-Limb® and Bebionic® hands both utilize an abduction/adduction movement of the thumb to change grasp types [5]. In these commercial prosthetic hands, the thumb motion is done by locking the thumb manually into different predefined abduction/adduction position.

In this paper, we describe a novel actuation mechanism scheme that allows two independent DOF to be controlled by a single actuator. The approach involves using one half of the actuator space (e.g. the "positive" rotation from zero) to control the opening/closing of the hand, and the other half (the "negative" rotation from zero) to move the thumb to select the grasp type. Since the overall flexion/extension of all the fingers of the hand, and the thumb abduction/adduction movements were considered the most important in achieving multiple grasp types, we have

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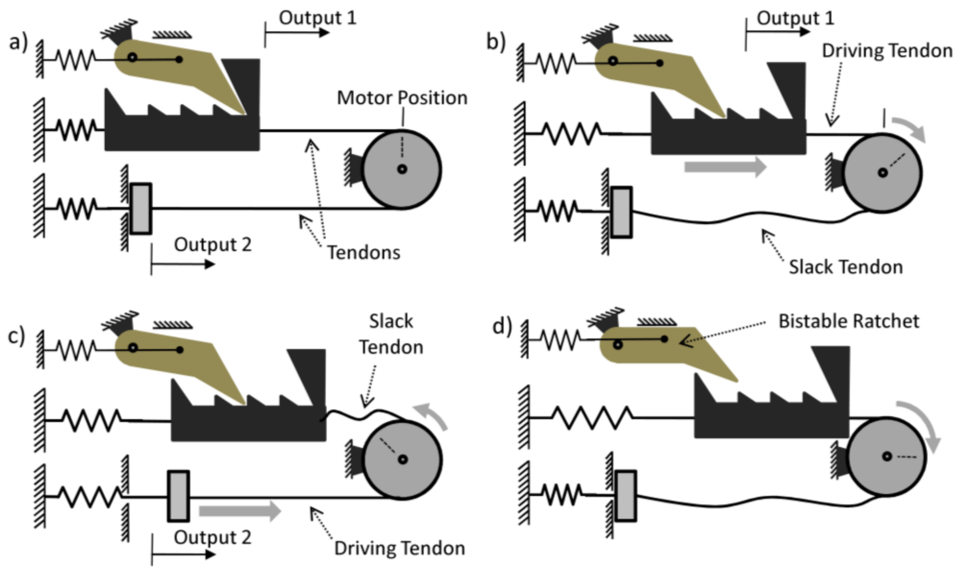

Fig. 2. This schematic diagram shows the method of controlling the position of output 1 and output 2 using the position of a single motor and a bistable ratchet. a) In the zero motor position the drive tendons to both outputs are tight. b) As the motor pulley turns clockwise, the motor pulls on a toothed plate to the desired position of Output 1. c) Output 2 is then controlled by moving the motor pulley in the counter-clockwise direction. d) To reset the position of the toothed plate, the plate is move to it's extreme position where the ratchet is pushed up to a stable position away from the plate teeth. When the toothed plate moved back to the zero position, it pulls the ratchet pawl back into contact with the teeth.

coupled these motions to a single actuator. Thus, we allow the hand to switch between four common grasp configurations without manual input from the user. It also allows the design to be packaged completely within the palm of a 50th percentile male size hand and reduces the weight and size of the device compared to a two-actuator system.

We begin the paper by reviewing previously described mechanisms providing similar functionality (section II). Next, we present the new design and show its implementation in a prototype hand. Finally, we discuss limitations of the approach and how this strategy could help improve practical prosthetic hands (section V).

II. Examples of Existing Systems

In this section we present a brief review of systems that focus on reducing the need for additional actuators to control a wide range of functions.

A. Underactuated Mechanisms

A common technique utilized in robotic hands is the use of underactuated coupling mechanisms. Underactuated mechanisms, as studied by [6,7] and others, are systems with more DOF than the number of actuators, but with each of those DOF passively coupled to the actuator. Although there is no direct control of each DOF, these systems control the sum of movement across all connected outputs. Examples of underactuated systems include floating pulley trees, differential gearing, and wiffle trees [7, 8]. Since the force distribution is determined by the coupling method and not a direct position coupling, external forces have an influence on the positions of the joints. This makes the technique attractive for use in grasping where the fingers are able to conform to an irregular shaped object.

B. Force Directing Actuation Systems

Another type of system is based on the idea of using a single large input that is coupled to all the outputs through individually controlled transmissions. The Cobot concept, developed at Northwestern University, uses multiple infinitely variable transmissions (IVT) that are each connected to a single drive element [9]. By independently changing the coupling ratio between the drive element and the output for each degree of freedom, any desired motion of the outputs can be achieved simultaneously. These systems have been demonstrated with six outputs controlling a 6-DOF Stewart Platform [9]. The advantage is that the main drive element can provide all of the power to a single output or split the power between all six outputs. If a system was developed with six individual motors of equivalent total power output, the system would be only be able to exert 1/6th of the power to a single output as compared to the Cobot architecture. Also, the weight of the 6-motor system would be larger than the weight of the Cobot system. The Cobot architecture has also claimed to provide power and weight savings when used in advanced prosthetic hands [10].

Other robotic hand designs use one main drive element connected to numerous outputs with a large underactuated differential mechanism. The differential mechanism distributes force equally across all the outputs. When not in contact with an object, the fingers of these hands will close in a fixed path. The designers then implement small electronic brakes on all the outputs. When one of the outputs is held fixed by the brake, the input forces are then split between the remaining free-spinning outputs [11]. Each individual output can be controlled by driving the input with all other outputs held fixed with the brake.

C. Gait Based Actuation Systems

One final method used in robotic hands is to couple multiple functions through a specific cycle of motion or "gait". An example of this type of system is seen in the KNU Hand [12] which incorporates a Geneva wheel [13], to

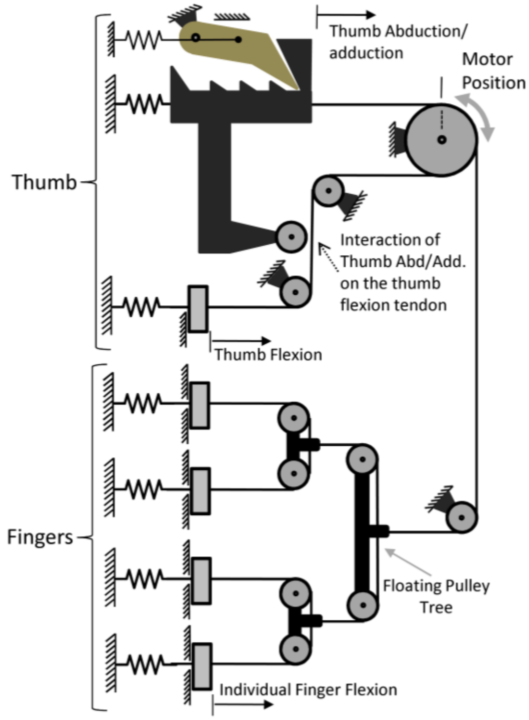

Fig. 3. Schematic of cable routing system used in the prototype hand. The thumb abduction/adduction position influences the relationship between the flexion of the thumb and four fingers by removing the slack in the thumb flexion cable with more adduction of the thumb.

couple the opening/closing of the thumb to the thumb abduction/adduction. The motion of the KNU thumb can be described as a single path that contains both thumb flexion/extension and abduction/adduction. Therefore, there is a direct mapping of input to output state. One of the key problems with moving the thumb along a single path of motion is that in order to change the thumb abduction position, the thumb must flex and extend completely in all abduction states leading up to the desired position.

III. Novel Thumb Actuation Method

A. Conceptual Design

The proposed thumbs actuation system is based on using a clockwise movement of the motor to affect one output while a counter-clockwise movement affects another output. A schematic diagram of the system is shown in Fig. 2. The system consists of two outputs that can be controlled with a single motor input position. As seen in Fig. 2 (a), when the motor is in the zero position, the drive tendons to the two outputs are tight. Any movement of the motor clockwise, shown in Fig. 2 (b) causes the toothed plate, (here serving as the position of Output 1) to move to the right. During this motion, a ratchet pawl is engaged in a set of teeth that locks the toothed plate in the most positive position. To affect Output 2, the motor is turned counterclockwise, as shown in Fig. 2 (c). Here the tendon connecting the motor and toothed plate becomes completely slack while the tendon connected to Output 2 is tight. In this configuration the movement of the motor corresponds with the motion of Output 2. To reset the position of Output 1, the toothed plate is moved to its maximum travel position through a clockwise motion of the motor. At this point a protrusion on the toothed plate pushes up on the ratchet pawl. The spring holding the ratchet pawl goes over center, (to the other side of the pivot point) and holds the ratchet up against a hard-stop, away from the teeth of the plate. The ratchet pawl is then pulled back against the teeth by a ramp at the front of the plate. Since the ratchet pawl is held by the spring in two stable positions, it is referred to as a bistable ratchet. This is the key feature that allows both outputs to be controlled with the same motor.

B. Implementation in Robotic Hand

To implement the actuation scheme in a hand, we first needed to make the two outputs of the system described in Fig. 2 represent the opening/closing of the fingers and the change in the thumb abduction/adduction angle. Fig. 3 illustrates how this was achieved within the architecture of the hand.

The motion described as Output 2 in Fig. 2, is replaced with the drive tendons that control the flexion of all the fingers. The index, middle, ring, and little fingers are connected through an underactuated floating pulley tree. The underactuated coupling lets the fingers passively adapt to the shape of objects in the grasp. The thumb flexion tendon is directly coupled to the first drive tendon of the pulley tree and thus not included in the differential.

The motion described as Output 1 in Fig. 2, controls the abduction/adduction position of the thumb. The rotational position of the thumb determines the type of grasp the hand will perform. One key observation when attempting to flex all fingers of the hand with a single actuation, was the difference in the thumb closing timing relative to the other fingers in the different grasp configurations. For example, when performing a lateral grasp, the thumb must wait until the fingers form a complete fist before closing to apply pressure to the side of the index finger. When performing a precision grasp, the thumb must close in sync with the index finger so they meet in the center. Fig. 3 shows a way to accommodate for the difference in thumb flexion timing in the four grasp configurations of the prototype hand. As the thumb abduction/adduction position is changed, an additional pulley interferes with the path of the thumb flexion cable. This tightens the thumb flexion cable when the thumb is moved toward a power grasp position. The size and spacing of the pulleys was modified until the desired effect was achieved for all grasp types.

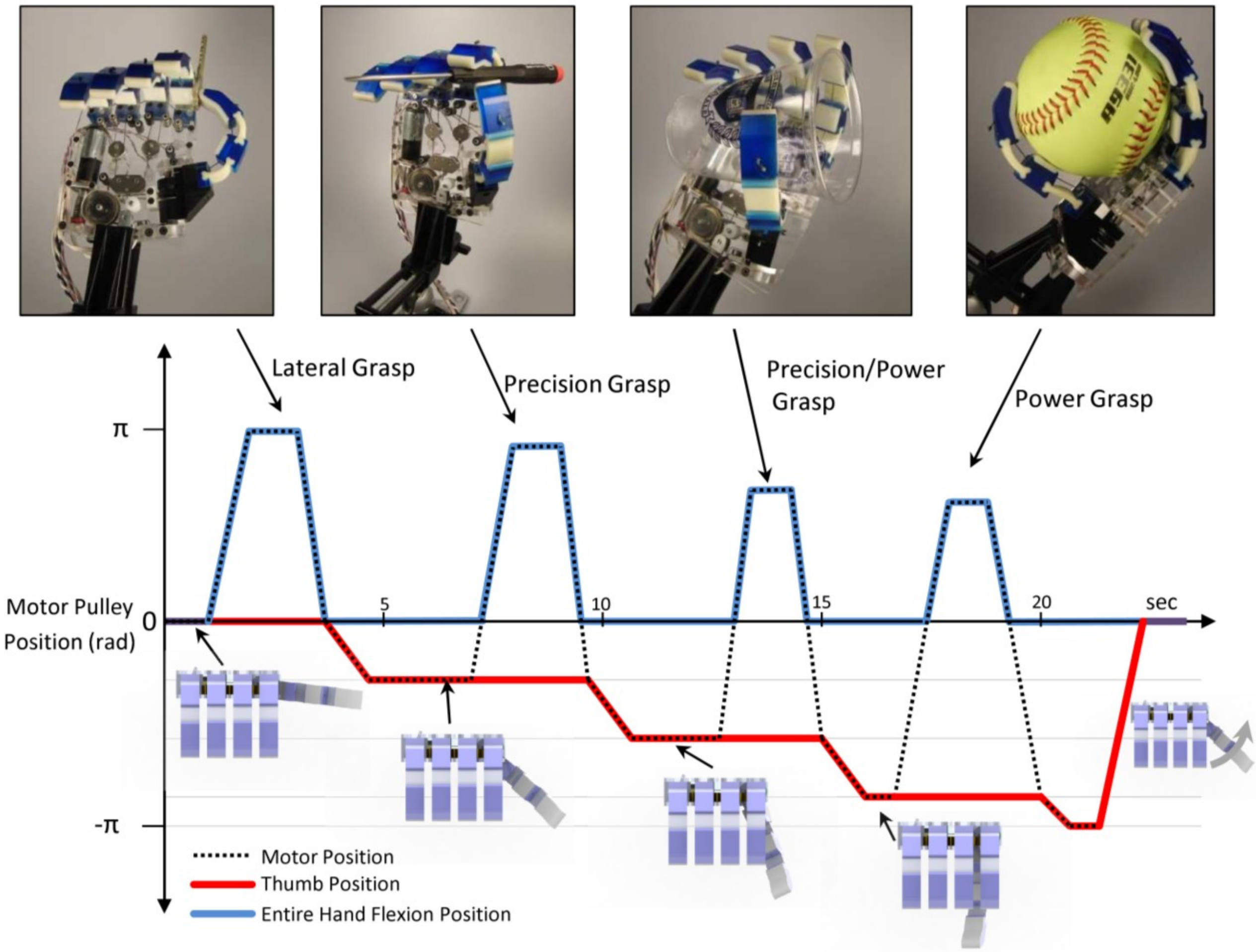

Fig. 4. The plots above show the general control method to preposition the thumb in the required abduction/adduction position and then execute a particular grasp type using one control input. The dotted line indicates the path taken by the motor pulley. The red and blue lines indicate the thumb position and the flexion position of the entire hand, respectively.

IV. Evaluation of Prototype Hand

A prototype hand was build to test the benefits of the proposed coupling strategy described in Sec. III.

A. General Construction

The palm of the hand was sized base on the 50% male right hand. It consists of two acrylic plates that make up the front and back of the palm. All actuation components are housed within the palm of the hand. The single DC motor, detailed in Table 1, is mounted vertically along the inside of the palm. It is connect through a set of worm gears to the motor drive pulley. The worm gear makes the system non-backdrivable and therefore able to maintain grasp force without continued current draw to the motor. The motor and transmission can be seen on the left side of the palm in Fig. 4 (far left).

The fingers of the hand are made through shape deposition manufacturing out of three types of polyurethane resin as detailed in [3]. Each finger has a proximal and distal flexure joint with a single actuation tendon spanning both joints. The thumb is connect to the palm through a Delrin® base (seen as the black block at the base of the thumb in Fig. 4, far left) which pivots on an abduction/adduction axis that is slightly angled toward the base of the middle finger. A rotational version of the linear bistable ratchet and pawl mechanism shown in Fig. 2 and 3 is attached to the bottom of the Delrin ® base and controls the abduction angle of the thumb. The rotational ratchet system, illustrated in Fig. 5, has four discrete abduction positions, corresponding to the desired thumb position for each grasp type.

The pulleys of the underactuated pulley tree (which drives the index, middle, ring, and little fingers) are machined from aluminum and have enough travel to allow the fingers to adapt to various object shapes. Table 1 shows the general specifications of the prototype hand. The grasp force and speed measurements were performed with 12V supply voltage.

B. Motion Sequencing and Time Delay

The control of the hand prototype uses simple position control when performing a selection of the thumb position, and can utilize position and/or force control when grasping on an object. Fig. 4 illustrates the necessary motor pulley movements to switch and perform all four grasp types. The red (light grey) line shows the position of the thumb as

Table I : Single Actuator Hand Specifications

Motor	4-Watt Maxon RE-max 17
Transmission	19:1 Planetary with 22:1 Worm gear reduction
Degrees of Freedom	11
Coupling Method	Floating Pulley Tree
Weight	350 grams*
Control Method	Off-board single-site EMG
Manufacturing Method	SDM Fingers with Acrylic palm
Grasp Force	5.1 N (Power Grasp) 4.7 N (Lateral Grasp)
Grasp Speed (Full Power Grasp)	0.9 sec
Grasp Type Transition Speed	0.8 sec 1.2 sec (power to lateral)

*without battery or control hardware

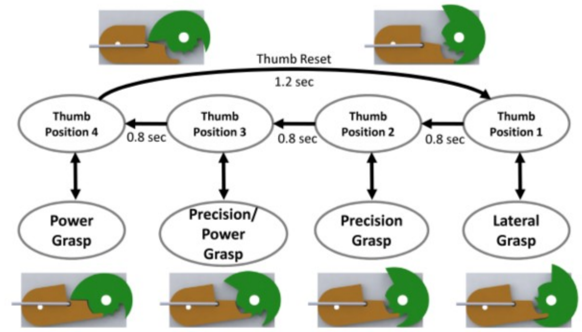

Fig. 5. State space representation of the control architecture for the single actuator prototype hand. The bistable ratchet state is also shown at each grasp type and reset sequence. The rotation of the green ratchet plate represents the abduction/adduction angle of the thumb.

related to the position of the motor (indicated by a black dotted line). The solid blue (dark grey) line shows the flexion position of all the fingers. The graph shows a sequence of performing each of the four grasp types in succession and returning the thumb to the lateral grasp position. It should be noted that due to the limitations of the actuation method there is a small time delay associated with switching between grasp types. This time delay is present even if the pretension length is changed since the hand must open completely before switching grasp types.

C. *User Control of Grasp Type and Closing*

To represent how an amputee may use this type of system we controlled both the transition from one grasp to the next and the closing\opening of the hand through a single EMG signal. The signal was taken from a single site on the forearm and a typical signal threshold was established. If the signal was above the threshold for greater than 200 msec, a closing of the hand was initiated until the signal was terminated. Any “twitch”, defined as an EMG signal above the threshold for less than 200 msec, caused the hand to either open the grasp to the zero position, or move the thumb abduction/adduction corresponding to the next grasp type. If a “twitch” signal was received while in a power grasp position, the thumb was returned to the lateral grasp location.

V. Discussion

The prototype single actuator hand demonstrated the practical implementation of the actuation scheme presented in Fig. 2 & 3 to reduce the number of actuators required in a functional robotic hand.

The hand was able to show a similar function to a hand with a separate actuator controlling the abduction/adduction position of the thumb. The weight of the components alone associated with the thumb abduction/adduction movement was approximately 25 grams. This included the added pulleys and the bi-stable ratchet system at the base of the thumb. The added weight associated with placing a second DC motor (same as in the prototype) at the base of the thumb is estimated to be 60 grams based on the weight of the motor and required transmission elements. Therefore, based on the weight of the necessary components, the strategy presented in this paper could account for a 35 gram improvement in the weight of the device (assuming similar overall hand construction). This 10% improvement in total device weight (not including the batteries and control system) must be compared to the reduced function as compared to a similar hand with two actuators.

One limitation of the system presented is that the thumb abduction/adduction position can only be altered while the hand is open. This prevents the hand from performing any form of in-hand manipulations that requires simultaneous movements. In the case of prosthetic terminal devices, in-hand manipulation is not necessary which indicates that the lack of simultaneous motion would only be detrimental to those wishing to use this system for robotic hand applications.

There is also a time-delay associated with switching between grasp types due to the nature of the actuation method. Fig. 5 illustrates a state-space representation of the hand. This mapping can be used to illustrate how to achieve the required grasp type. Unlike a hand with fixed coupling (e.g. [8]), the system does not have a single variable that can describe the entire state of the system. The small images show the position of the rotary bistable ratchet at each state of the system which correspond to the different grasp types. From each thumb position, the user can either perform that particular grasp type associated with that thumb position, or move to the next thumb position in the sequence. The hand system requires 0.8 sec to move the abduction angle of the thumb and return to the motor pulley zero position, ready to perform the next grasp type. To transition from a precision grasp to a lateral grasp can take as much as 2.8 sec. This delay in the ability to perform the desired grasp type may prove too long for the system to be used in a prosthetic hand.

VI. Conclusion

In this paper, we showed a marginal weight benefit of a proposed coupling strategy to enable a prototype hand to perform four grasp types with a single motor. Obvious limitations were identified including the lack of simultaneous motion of the two outputs as well as a long time delay associated with switching between grasp types. Since weight is known to be an important factor in the adoption of terminal devices, this mechanical system could help in the development of better, lighter, terminal devices.

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