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STATIC ANALYSIS OF SINGLE-INPUT/MULTIPLE-OUTPUT TENDON-DRIVEN UNDERACTUATED MECHANISMS FOR ROBOTIC HANDS

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ABSTRACT

Considering the many advantages of underactuation in anthropomorphic hands, such as lightness, ease of control and compactness, it is of interest to develop mechanisms that aim at achieving underactuation between the fingers. This paper presents several tendon-driven underactuated mechanisms that can drive four outputs from one input. These mechanisms could typically be used to drive four fingers of an underactuated hand from a single input. Among these mechanisms, some are built by combining one-input/two-output differential mechanisms, while others are fully integrated systems of pulleys. For each mechanism, a static analysis is presented. Then, a discussion based on the static analysis and experimentation on models highlights their strengths and weaknesses. Finally a new anthropomorphic hand used as an experimental platform to test these mechanisms is introduced.

INTRODUCTION

Underactuated hands constitute a very promising design avenue for future prosthetic and robotic applications. Indeed, given the complexity and the number of articulations in a somewhat versatile hand, independent actuation of all joints leads to a very large number of actuators and is not a realistic approach. In fact, even biological systems do not generally allow independent motion of all the joints. Underactuation has been used in numerous finger/hand designs (see for instance [1] for a review).

Although most of the literature on underactuation focusses mainly on the design of underactuated fingers, it is clear that the introduction of underactuation between the fingers is also a very promising concept. In this context, it is desired to drive a set of fingers — typically 3 to 5 fingers — using a common input. Hence, the underactuation of the fingers is based on a single-input/multiple-output mechanism that transmits the actuation power to the fingers while allowing an adaptive distribution to take place, depending on the object to be grasped. This principle was demonstrated in many prototypes. For instance, seesaw and bar mechanisms are used in [2–5], planetary gear differentials are used in [6, 7], a pneumatic differential is used in [8, 9] and springs placed in series with the actuation of each finger are used in [10, 11]. Moreover, many underactuated mechanisms including tendons have been proposed. For instance, pulleys are used in [12, 13], while seesaws are used in [14] and a floating triangular plate is used in [15]. The force distribution analysis of multiple-finger underactuated systems was studied in [1, 16] and a general mathematical framework was developed. Design solutions based on linkages, gears, tendons and fluids were studied and it was shown that a proper geometric synthesis of these components can produce the desired force distribution properties.

In this paper, the focus is placed on tendon-driven underactuated hands. The context of the work reported here is the development of five-finger humanoid robotic hands with one or very few actuators [13]. The applications for such systems include prosthetics or hands for humanoid robots. In such applications — especially in prosthetics — weight minimization, as well as limited independent inputs, is of the utmost importance, which motivates the minimization of the number of actuators. This paper presents several tendon-driven underactuated mechanisms that can drive four outputs from one input. These mechanisms could typically be used to drive four fingers of an underactuated hand from a single input. Among these mechanisms, some are built by combining one-input/two-output differential mechanisms, while others are fully integrated systems of pulleys. For each mechanism, a static analysis is presented. Then, a discussion based on the static analysis and experimentation on models highlights their strengths and weaknesses. Finally a new anthropomorphic hand used as an experimental platform to test these mechanisms is introduced.

SINGLE-INPUT/MULTIPLE-OUTPUT UNDERACTUATED MECHANISMS

As mentioned above, several techniques can be used to transmit forces to multiple outputs from a single input. In this paper, only tendon-driven systems are considered and mechanisms are proposed.

The mechanisms presented in the following subsections allow the transmission of one input to four underactuated outputs. A static analysis is performed on each of the proposed mechanisms in order to determine the ratio between the output and input forces. It is important to note that the analysis is based on the assumption that the friction between the cables and pulleys can be neglected. This approach is taken in order to simplify the equations and provide insight into the mechanisms. However, comments on the effect of friction will be given based on the observation of experimental models.

In what follows, the input force is noted F_a while the output forces are noted $F_i, i = 1, \dots, 4$. It is assumed that four outputs are used. This assumption arises from previous work on five-finger anthropomorphic hands [13]. Indeed, in the latter reference, a five-finger hand was driven using a single actuator. Four of the fingers were underactuated while the fifth finger (the thumb) was directly coupled with the input. This principle is discussed in the next section. Nevertheless, it should be noted that the assumption of having four outputs is not restrictive and the mechanisms proposed here could be applied to a different number of outputs.

The mechanisms are now described and the results of the static analysis are given.

Double-Stage Fixed-Pulley Mechanism

This underactuation mechanism (Figure 1) consists of tendons running in nine pulleys, six of them being fixed while three are floating. Also, a perfect symmetry of the mechanism is assumed. This is achieved partly through the fixed pulleys that guide the cables exactly at the right places. The forces in the mechanism are given by

$$F_1 = F_2 = \frac{F_a}{4 \sin \alpha_4 \sin \alpha_2} \tag{1}$$

$$F_3 = F_4 = \frac{F_a}{4 \sin \alpha_4 \sin \alpha_6} \tag{2}$$

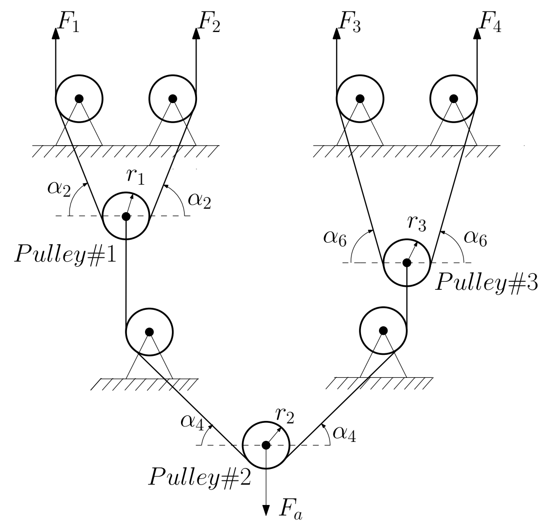

FIGURE 1. SCHEMATIC ILLUSTRATION OF THE DOUBLE-STAGE FIXED-PULLEY MECHANISM.

The motion of the mechanisms is determined by the restrictions at the outputs. The different situations are presented here:

If all four outputs have the same restriction, the actuation causes an equal downward displacement of the three floating pulleys. This provides a force equal to each output, but not constant during the actuation.

If output 1 is blocked, the three pulleys can still move downward because the cable connecting outputs 1 and 2 is free to move in the floating pulley 1. It should be noted that the force available at the four outputs remains the same in this case since the winding of the tendons on pulleys 1 and 3 is identical.

In the case where outputs 1 and 2 are blocked, the mechanism is still working, but winding on the floating pulleys 1 and 3 is no longer the same. Indeed, floating pulley 1 is now fixed in translation and it is the cable that connects that pulley and pulley 3 which runs on floating pulley 2 to allow the mechanism to continue its movement. The force available at outputs 1 and 2 is now different from that available at outputs 3 and 4.

If outputs 1 to 3 are blocked, the mechanism can still move downward as the cable connecting outputs 3 and 4 is free to move on floating pulley 3. The distribution of the forces at the outputs is exactly as in the previous case.

Finally, if the outputs 1 and 4 or 2 and 3 are blocked, the three floating pulleys move downward and the force at the 4 outputs is equal.

This mechanism has been implemented in the hand presented in [13]. In order to stabilize the floating pulleys, they were guided by slides, which introduced a significant amount of friction. Removing the slides from the floating pulleys to reduce friction is very effective, but the pulleys must not tend to flip over, in order to keep the cable around the pulleys. Figure 2 shows the part used to make such an arrangement. The fact that there is a distance between the contact point on the pulley and the actuating location guarantees the stability of the assembly. Indeed, whenever there is a small misalignment of the pulley, this part will tend to rotate to align the contact point on the pulley and the point of actuation. Also, the cable or tendon is trapped in the assembly so it is always at the right place.

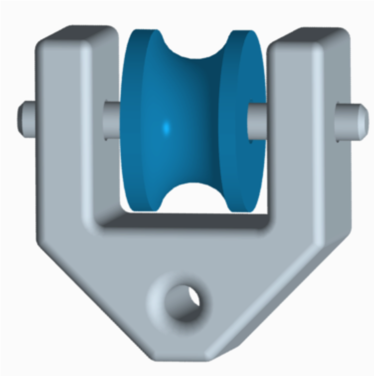

FIGURE 2. CAD MODEL OF THE PART USED TO ENSURE STABILITY.

This mechanism is very compact and allows cables to exit at the right place at its upper end. However, there is a lot of friction in the mechanism, mainly because of the numerous fixed pulleys. This friction could be reduced by using better pulleys. It is noted that the forces in the outputs are not constant during the actuation of the mechanism since the winding on the pulleys is changing. More precisely, as the mechanism is pulled, α_i increases. Therefore, the ratio F_i/F_a increases. When $\alpha_i = \pi/2$, then $F_i = F_a/4$.

Double-Stage Floating-Pulley Mechanism

This mechanism (Figures 3 and 4) is fully floating. It is composed of cables running in three floating parts including two pulleys each. Its geometry is very similar to that of the preceding mechanism, but it requires only six pulleys and it is also floating. It is noteworthy that for all cases, the four outputs have the same force available. Indeed,

$$F_1 = F_2 = F_3 = F_4 = \frac{F_a}{4} \quad (3)$$

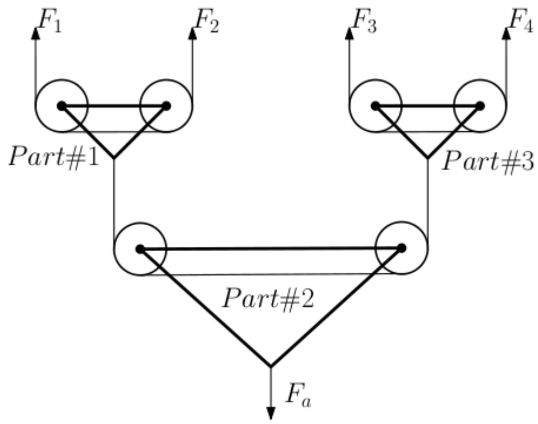

FIGURE 3. SCHEMATIC ILLUSTRATION OF THE DOUBLE-STAGE FLOATING-PULLEY MECHANISM.

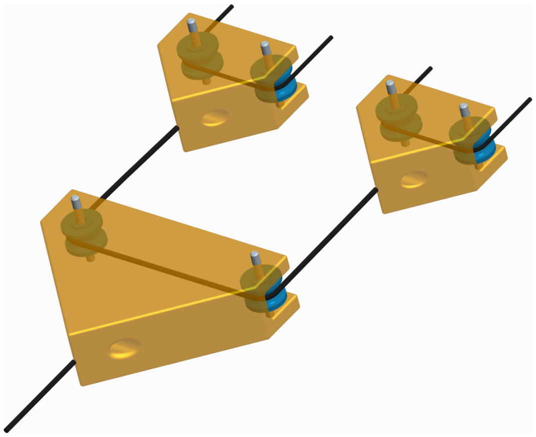

FIGURE 4. CAD MODEL OF THE DOUBLE-STAGE FLOATING-PULLEY MECHANISM.

When the four outputs move equally, each of their motion equals the motion of the input. The motion of the mechanism is determined by the restrictions at the outputs. The different situations are presented here:

If all four outputs have the same restriction, the actuation causes an equal downward displacement of the three floating parts and the cables are not moving on the pulleys.

If output 1 is blocked, the three parts are still moving as the cable connecting outputs 1 and 2 is free to move in the floating part 1. The underactuation is then performed between two consecutive outputs.

In the case for which the outputs 1 and 2 are blocked, the floating part 1 is no longer moving and the cable that connects it with floating part 3 is moving through floating part 2 to allow the mechanism to continue its movement.

If outputs 1 to 3 are blocked, the mechanism is still allowed to move downward as the cable connecting the outputs 3 and 4 is free to move in floating part 3.

Finally, if outputs 1 and 4 or 2 and 3 are blocked, the three floating parts move downward, with the cables moving freely in parts 1 and 3.

The floating parts used in this mechanism include two pulleys each, and they use the same principle as the floating parts of the preceding mechanism to ensure a good stability. Also, their triangular shape ensures the symmetry of the mechanism.

Since the mechanism is fully floating and is only composed of 6 pulleys, it generates very little friction. A slight friction in the pulleys has the effect of helping the synchronization of the outputs if none is stopped. Another important advantage of this mechanism is that it provides an equal force at each output in all cases of underactuation. The two pulleys included in the floating parts could be replaced by a single larger one, but the configuration shown is much more compact. Another advantage of being floating is that it facilitates the assembly since it doesn't need to be set anywhere. It is noted that the mechanism implemented in the hand presented in [12] has similarities with the two previous mechanisms.

Double-Stage Floating-Seesaw Mechanism

This mechanism is also fully floating. It is composed of cables attached to small triangular seesaws. In Figure 5, note that if the angle θ_i of a given triangle is negative, it will be oriented towards the bottom instead of the top. This is affecting the kinematics of the mechanism for the cases of underactuation between the different outputs, as described in the following equations. To simplify the analysis, lateral movements between the triangles are neglected, i.e., the cables are assumed to remain vertical. This assumption is valid as long as the lateral displacements are significantly smaller than the length of the cables. We have:

$$F_1 = \frac{c_{p1}c_{p2}F_a}{c_{p1}c_{p2}+c_{p1}c_{m2}+c_{m1}c_{p2}+c_{m1}c_{m2}} \tag{4}$$

$$F_2 = \frac{c_{m1}c_{p2}F_a}{c_{p1}c_{p2}+c_{p1}c_{m2}+c_{m1}c_{p2}+c_{m1}c_{m2}} \tag{5}$$

$$F_3 = \frac{c_{p3}c_{m2}F_a}{c_{p3}c_{p2}+c_{p3}c_{m2}+c_{m3}c_{p2}+c_{m3}c_{m2}} \tag{6}$$

$$F_4 = \frac{c_{m3}c_{m2}F_a}{c_{p3}c_{p2}+c_{p3}c_{m2}+c_{m3}c_{p2}+c_{m3}c_{m2}} \tag{7}$$

where

$$c_{pi} = \cos\left(\alpha_i + \theta_i\right) \quad i = 1,2,3 \tag{8}$$

$$c_{mi} = \cos\left(\alpha_i - \theta_i\right) \quad i = 1,2,3 \tag{9}$$

When the triangular seesaw rotates, the two output forces will not be equal because the lever arms are changing. Figure 6 summarizes the effect of angles θ_i and α_i on the ratio of the two output forces of a triangular seesaw. As a remark, if $\theta_i = 0$ or if $\alpha_i = 0$, then the two output forces are equal.

It is important to mention that it is preferable to let the triangles point downward ($\theta_i < 0$), as presented in Figure 7, since the mechanism is more likely to stay in an equilibrium configuration if a resistive force (for example friction) is slightly larger at one of the outputs, as illustrated in Figure 8. Then, an external perturbation will only slightly desynchronize the output positions. This is explained by the fact that the seesaw will apply more force on the more resisted output. On the other hand, if the triangles point upward ($\theta_i > 0$), as illustrated in Figure 9, the seesaw will flip on its side as soon as the resisting force is slightly larger at one of the outputs, as illustrated in Figure 10. Then, a small external perturbation will strongly desynchronize the output positions. This is explained by the fact that the seesaw will apply a smaller force on the output with more resisting force.

When the four outputs move equally, each of their motion equals the motion of the input. The actual motion of the outputs will be determined by the restrictions. The different situations are presented here:

If all four outputs have the same restriction, the actuation causes an equal downward displacement of the three triangles and the force available at each of the four outputs is equal.

If output 1 is blocked, triangle 1 rotates and moves downward to allow the continuity of the movement. The underactuation is then performed between two consecutive outputs.

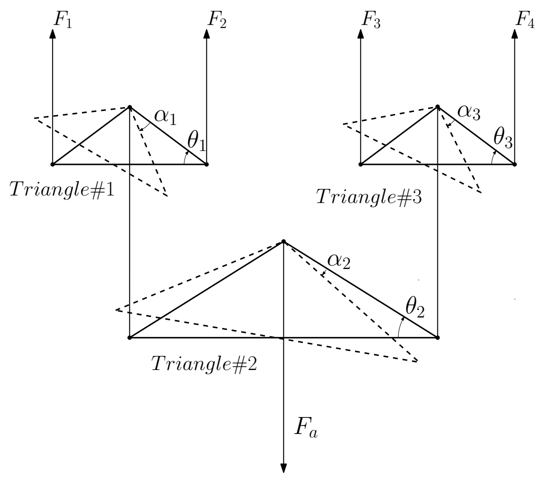

FIGURE 5. SCHEMATIC ILLUSTRATION OF THE DOUBLE-STAGE FLOATING-SEESAW MECHANISM.

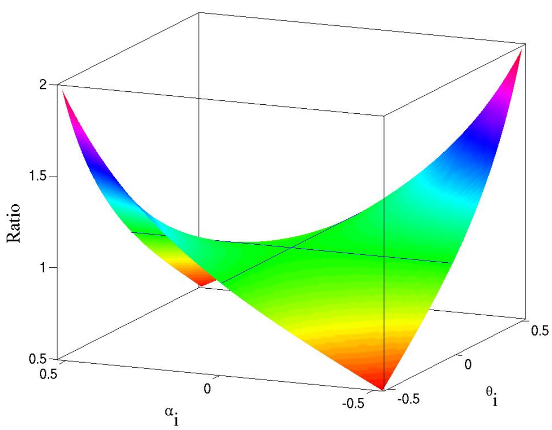

FIGURE 6. RATIO OF THE OUTPUT FORCES OF A TRIANGULAR SEESAW AS A FUNCTION OF THE TRIANGLE GEOMETRY (θ_i) AND ORIENTATION (α_i).

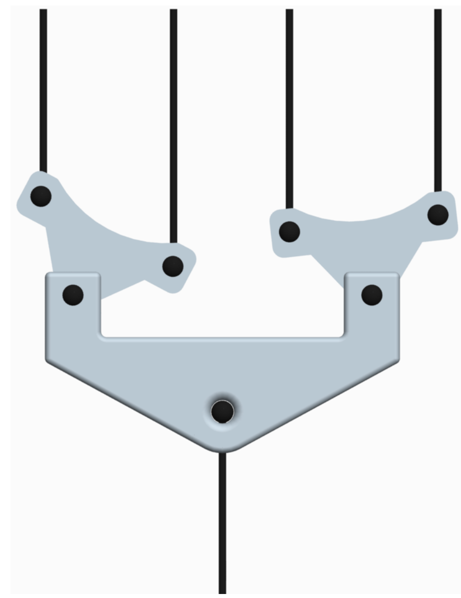

FIGURE 7. CAD MODEL OF THE DOUBLE-STAGE FLOATING-SEESAW MECHANISM WITH θ_i NEGATIVE.

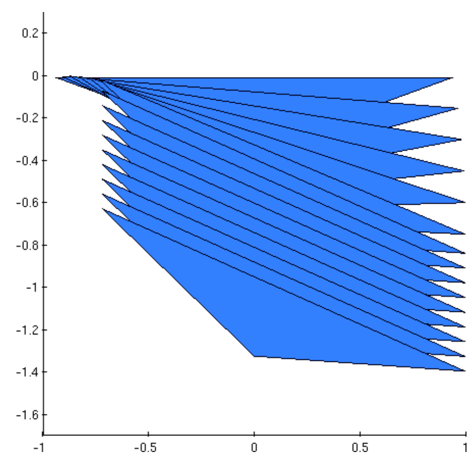

FIGURE 8. REACTION OF A SEESAW TRIANGLE WITH θ_i NEGATIVE.

In the case for which outputs 1 and 2 are blocked, triangle 1 is no longer moving and triangle 2 rotates on itself while moving downward.

If outputs 1 to 3 are blocked, the triangle rotates to allow the mechanism to move downward.

Finally, if the outputs 1 and 4 or 2 and 3 are blocked, triangles 1 and 3 rotate and move downward.

The fact that this mechanism is floating and does not require the use of pulleys produces almost no friction, even during underactuation. On the other hand, the fact that the output forces are not always equal may be a drawback for some applications. Also, during the rotation of the triangles, the cables move laterally which may have undesirable side effects if the rotation is excessive. Finally, the range of underactuation possible with this mechanism depends on the distance between the outputs. Indeed, the smaller the seesaws, the smaller the range of relative motion because their rotation generates small displacements of the cables. In practice, a small negative θ_i is suggested. It allows to maintain the synchronization of the mechanism when small perturbations, such as friction, are applied, but yields relatively equal forces on four outputs locked at different positions. It is noted that the mechanism presented in [14] is similar to this mechanism. In the latter reference, the use of triangular seesaws, named dogleg links, is briefly discussed.

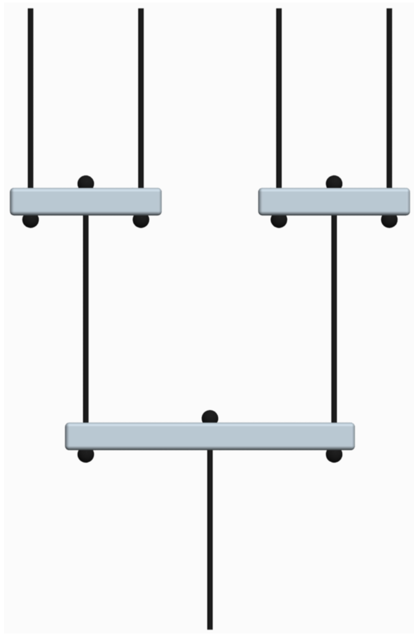

FIGURE 9. CAD MODEL OF THE DOUBLE-STAGE FLOATING-SEESAW MECHANISM WITH θ_i POSITIVE.

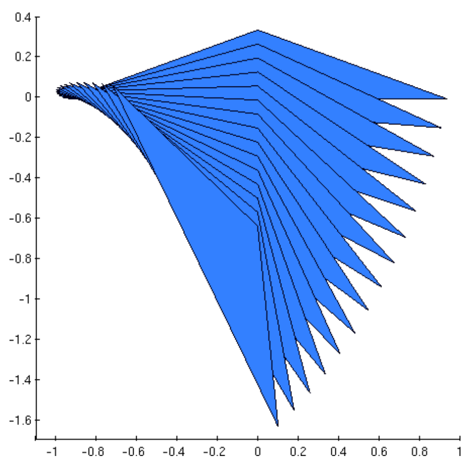

FIGURE 10. REACTION OF A SEESAW TRIANGLE WITH θ_i POSITIVE.

Fixed Closed-Loop-Cable Mechanism

This mechanism (Figure 11) consists of ten pulleys, five of which are floating while the other five are fixed. Its particularity is that it includes a closed-loop cable.

If all four outputs have the same restriction, the actuation causes an equal downward displacement of the four floating pulleys. Indeed, the cable loop tends to minimize its tension by bringing down theses pulleys. If the four floating pulleys are fixed, the mechanism stops and the tension in the cable increases directly with the operating force. Note that in this case, the four outputs have the same force.

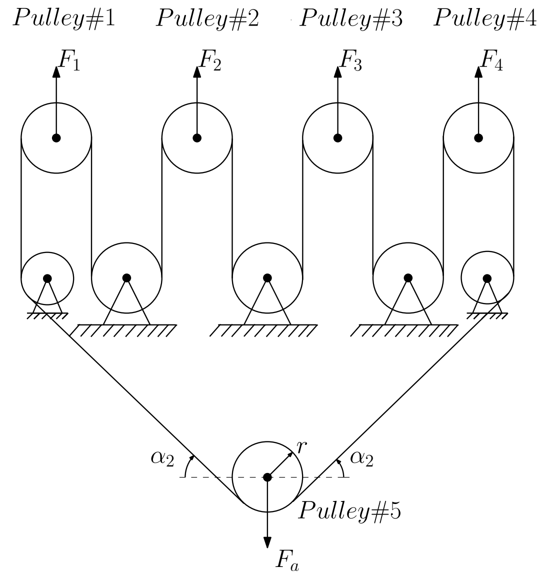

FIGURE 11. SCHEMATIC ILLUSTRATION OF THE FIXED CLOSED-LOOP-CABLE MECHANISM.

For other cases where one or more output(s) is/are blocked, the mechanism still moves because the cable is free to move between the pulleys. In other words, even if some floating pulleys (1 to 3) are fixed, the other ones can continue their downward movement naturally. In all cases, the force is equal at each output with this mechanism. That is,

$$F_1 = F_2 = F_3 = F_4 = \frac{F_a}{\sin \alpha_2} \tag{10}$$

For a given actuation force, this mechanism provides greater output forces than the other mechanisms presented so far. Indeed, the floating pulley's free body diagram shows that inputs and output force is twice as large as the tension in the cable. When $\alpha = \pi/2$, $F_1 = F_2 = F_3 = F_4 = F_a$. From the principle of virtual work, the displacement of the input is then four times the displacement of the outputs. This can be a drawback when this distance needs to be small. Also, experimentation has shown that the friction in the fixed pulleys does not have an equivalent effect on each output. This leads to a poor synchronization of the mechanism: floating pulleys 1 and 4 move downward before the other two. The next mechanism (partially floating closed-loop-cable-mechanism) will provide a solution to this problem. Finally, the force of the four outputs is not constant during the operation because the winding on floating pulley 5 is not constant.

Partially Floating Closed-Loop-Cable Mechanism

This mechanism (Figure 12) is almost identical to the preceding one, but the middle fixed pulley has been replaced by a floating one. The latter is now directly operated and that completely solves the friction problem observed in the preceding mechanism. Operating two pulleys instead of one decreases the tension in the cable and thereby, the force at the four outputs. Indeed, we now have

$$F_1 = F_2 = F_3 = F_4 = \frac{F_a}{1+\sin\alpha_2} \tag{11}$$

When $\alpha = \pi/2$, $F_1 = F_2 = F_3 = F_4 = F_a/2$. From the principle of virtual work, the displacement of the input is then two times the displacement of the outputs. The operation is the same as in the preceding mechanism. In practice, this mechanism works better than the fixed closed-loop-cable mechanism.

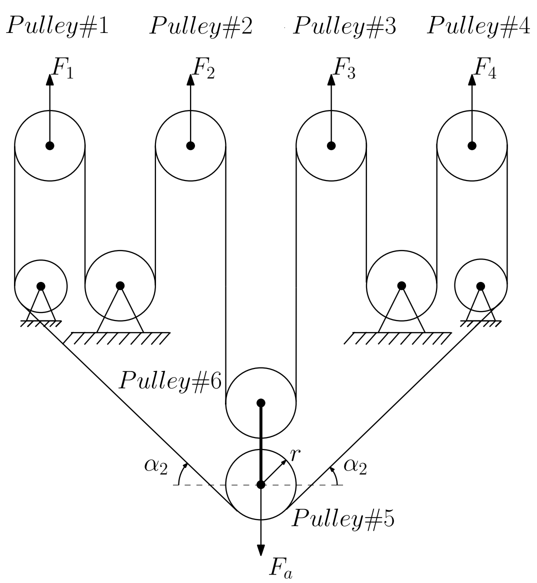

FIGURE 12. SCHEMATIC ILLUSTRATION OF THE PARTIALLY FLOATING CLOSED-LOOP-CABLE MECHANISM.

Floating Closed-Loop-Cable Mechanism

This mechanism (Figures 13 and 14) closely resembles the last two mechanisms presented above, but it is fully floating. A large floating part includes five pulleys in which a closed-loop cable runs with the other four floating pulleys. It is noteworthy that for all cases, the four outputs have the same force available, that is

$$F_1 = F_2 = F_3 = F_4 = \frac{F_a}{4} \tag{12}$$

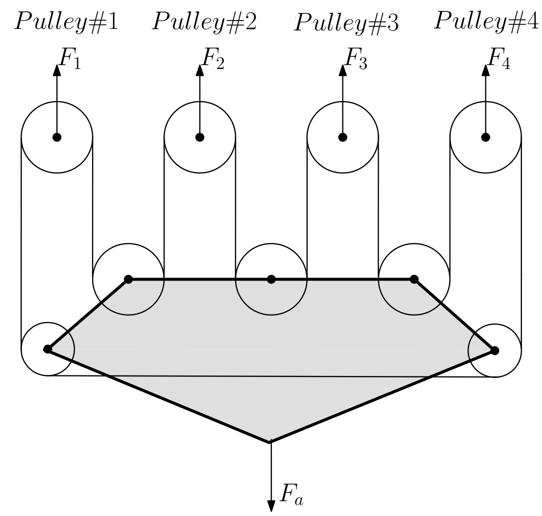

FIGURE 13. SCHEMATIC ILLUSTRATION OF THE FLOATING CLOSED-LOOP-CABLE MECHANISM.

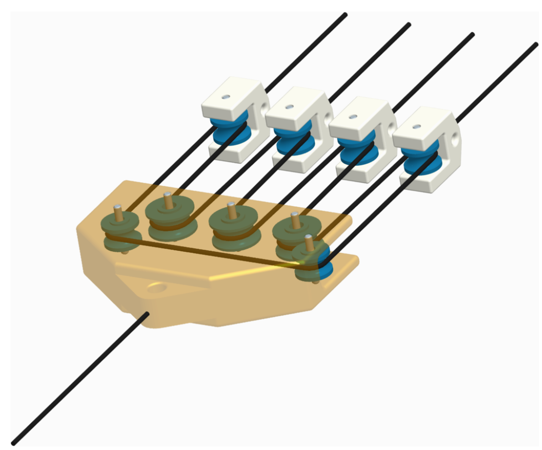

FIGURE 14. CAD MODEL OF THE FLOATING CLOSED-LOOP-CABLE MECHANISM.

If all four outputs have the same restriction, the actuation causes an equal downward displacement of the entire mechanism and the cable is not running through the pulleys. For other cases of underactuation, the operation is substantially the same as for the fixed closed-loop-cable mechanism.

This is the most compact mechanism presented so far. One of its great advantages is that it gives equal and constant forces to four outputs, even during underactuation between different outputs. Also, there is no friction when there is no underactuation since the cable is not running over the pulleys. On the other hand, this mechanism generates significant friction when restrictions on outputs are not identical.

INTRODUCTION OF AN ADDITIONAL COUPLED OUTPUT

The mechanisms presented so far include four completely underactuated outputs, i.e. without coupling between them. It is interesting in some applications to couple different outputs in order to predict more accurately their relative positions. For each of the six previous mechanisms, a fifth output coupled directly with the input can be added. Figure 15 illustrates this principle. For example, this type of arrangement can be very useful for the application of an underactuated hand in order to couple the thumb with the four other fingers. Figure 16 shows this application using the double-stage floating-seesaw mechanism presented above. Because of F_5, the remaining input force for the underactuation mechanism F_a' is given as

$$F_a' = F_a - F_5 \tag{13}$$

The value of F_5 depends on the external forces applied on the system. Also, it is noteworthy that if the fifth exit is blocked, the entire mechanism is also blocked because it is directly connected with the actuation. In a prosthetic context, if the thumb makes contact with an object, the prosthesis will slightly move relative to the object in order to allow the thumb (and the other fingers) to continue the closing action until the object is correctly grasped. It is noted that the actuation of the thumb was coupled in the three fingered prosthetic hand presented in [10].

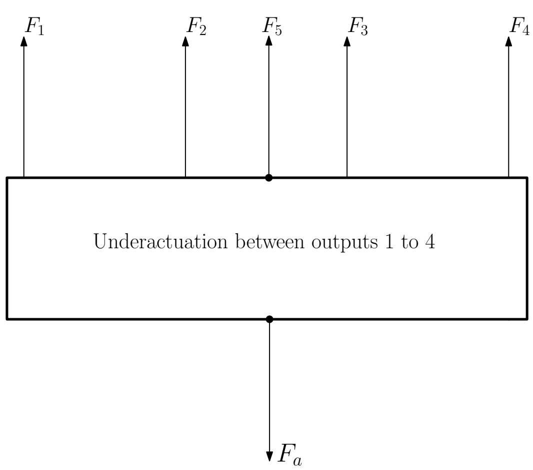

FIGURE 15. SCHEMATIC ILLUSTRATION OF THE ADDITION OF A 5th COUPLED OUTPUT.

APPLICATION TO A PROSTHETIC HAND

As shown in [13], the underactuation of the four fingers and the coupling of the thumb with the actuation is a promising avenue in the context of prosthetic hands. This approach provides stability while allowing enough flexibility in the grasps.

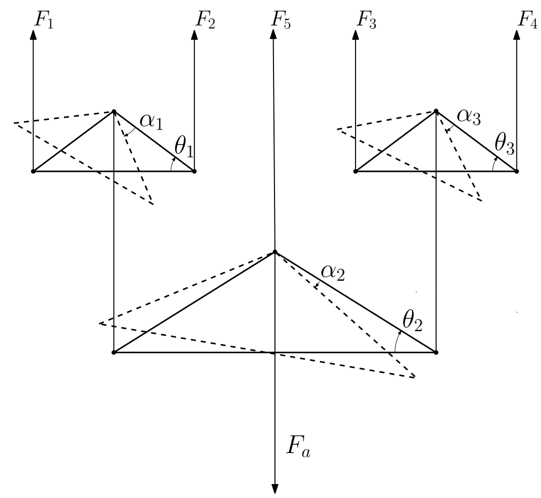

FIGURE 16. SCHEMATIC ILLUSTRATION OF THE DOUBLE-STAGE FLOATING-SEESAW MECHANISM WITH AN ADDITIONAL COUPLED OUTPUT.

The mechanisms presented above are all potential candidates for this application. They are compact, relatively simple and they provide a well balanced distribution of the forces between the fingers. Moreover, as shown in the preceding section, it is possible to add a coupled output (a thumb). From the static analyses presented above, it is clear that the geometry of the mechanisms has a definite impact on the force transmission properties. Therefore, the geometric design of the mechanisms is key to a proper behaviour of the hand.

The results of this work were applied to the design of a five-finger anthropomorphic prosthetic hand. The hand is illustrated in Figure 17. A single input is used and the actuating force is distributed among the four fingers using, for example, the mechanism referred to above as a double-stage floating-seesaw mechanism. Also, a fifth output — the thumb — is directly coupled with the input, as shown in Figure 18. The quality of the grasp obtained from each of the mechanisms is still to be tested.

CONCLUSION

This paper proposed several single-input/multiple-output tendon-driven underactuated mechanisms that have the capability to connect one input to several outputs while allowing underactuation between them. These mechanisms have been developed in the context of underactuated prosthetic hands. They are designed to provide underactuation between the fingers of a hand. A simple static analysis was presented for each of the mechanisms and it was shown that a proper geometric design leads to a well balanced distribution of the forces between the

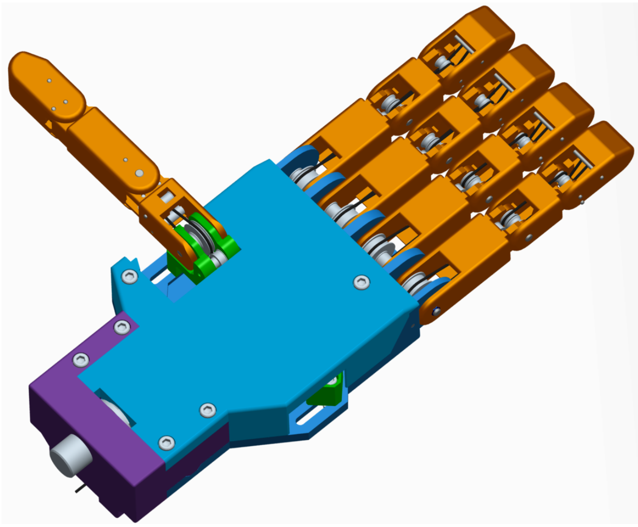

FIGURE 17. CAD MODEL OF THE ANTHROPOMORPHIC PROSTHETIC HAND.

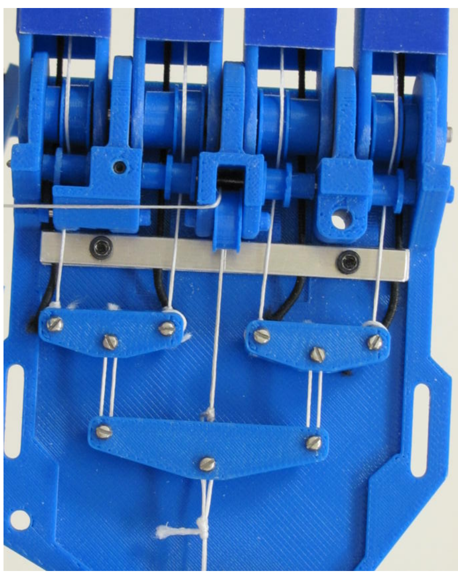

FIGURE 18. PHOTOGRAPH OF THE DOUBLE-STAGE FLOATING-SEESAW MECHANISM WITH θ_i NEGATIVE INSTALLED IN THE ANTHROPOMORPHIC PROSTHETIC HAND. THE THUMB HAS BEEN REMOVED FOR CLARITY. HOWEVER, ITS DIRECT COUPLING WITH THE INPUT CAN BE SEEN.

outputs. The introduction of an additional coupled output was also discussed. Finally, the implementation of one of the proposed mechanisms in an underactuated five-finger anthropomorphic hand was briefly described. The prototype of the hand can also serve as a test bench for the proposed mechanisms. Future work includes the systematic testing of the proposed hand in representative grasping tasks as well as the development of other underactuation mechanisms.

ACKNOWLEDGEMENT

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