A SINGLE-ACTUATOR ADAPTIVE GRIPPER WITH AN INTEGRATED SUCTION CUP

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ABSTRACT

Automated pick and place systems sometimes have to work within cluttered environments such as bins, shelves and boxes. These narrow spaces can be difficult to navigate to pick an object with a multi-fingered gripper. These grippers have a sturdy grasp on the object but need access to opposite sides of the object for grasping. Vacuum grippers only require access to one face of the object for grasping but generally result in weaker grasps on the object. In this research we explore different approaches to combine these two technologies in a single-actuator adaptative gripper. The most promising concept is then developed into a detailed design.

Keywords: Gripper; Linkage; Vacuum gripper; Suction cup; Hybrid grasping; Robot hand.

PRÉHENSEUR ADAPTATIF ACTIONNÉ PAR UN SEUL MOTEUR ET AVEC VENTOUSE INTÉGRÉE

RÉSUMÉ

Les systèmes automatisés de manipulation d'objets doivent parfois travailler dans des espaces encombrés comme des bacs, boîtes et étagères. Ces espaces exigus peuvent être difficiles d'accès pour un préhenseur à plusieurs doigts. Ces préhenseurs permettent des prises solides mais requierent l'accès à deux côtés opposés de cet objet. Les préhenseurs à ventouses requierent seulement l'accès à une face de l'objet pour le saisir mais ont une prise généralement moins solide sur l'objet. Dans cette recherche, nous explorons différentes approches pour combiner ces deux technologies dans un préhenseur adaptatif actionné par un seul moteur avec ventouse intégrée. Le concept le plus prometteur est ensuite développé en un prototype qui reste à venir.

Mots-clés : Préhenseur ; Mécanisme articulé ; Préhenseur à vide ; Ventouse ; Préhenseur hybride ; Main robotique.

1. INTRODUCTION

1.1. Background

Automated pick-and-place systems are time efficient and reduce the need for manual repetitive labour. Therefore they are used in many industries such as shipping, recycling, food production and many more. In large distribution centres, objects of different sizes, shapes and weights may be placed in the same bin or side by side on the same shelf. The proximity of these objects makes it difficult for a robotic hand to pick a specific object without interfering with its neighbours or wall. Introducing clearance space in between objects would require more shelf and space.

The two main technologies for picking objects are vacuum and finger grippers. Vacuum grippers can pick up objects in cluttered environment without needing to access the sides of the object. However, the grasp strength is smaller than that of a finger gripper, limiting their application to lighter objects and lower accelerations. Finger grippers offer strong and secure grasps on objects, but require clearance around them and also often fail when picking thin objects lying flat.

The combination of these two technologies could exploit their respective strengths without their disadvantages. One could then perform pick and place in cluttered environments and have the option to use the end effector either as a vacuum gripper or, as a finger gripper or as both at the same time without the need to change the end effector. The latter grasping method will be referred to as combined grasping.

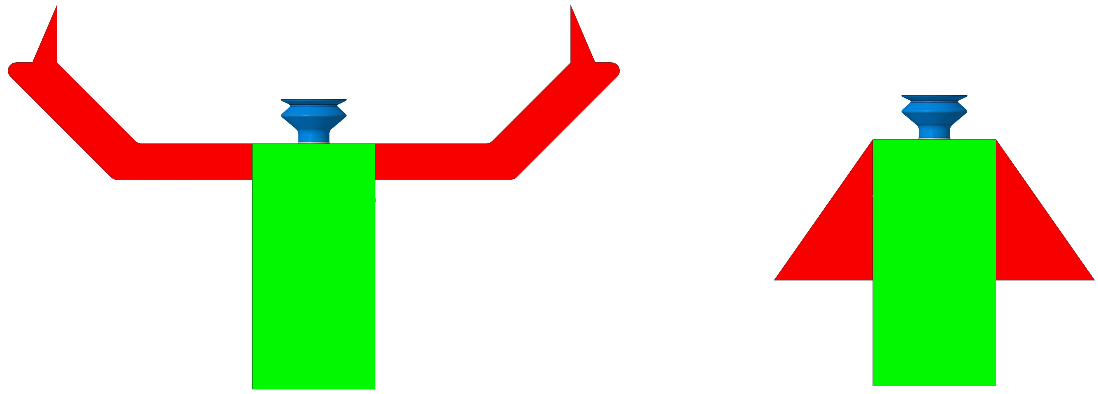
1.2. Literature review

Several studies have approached this problem by combining a suction cup and a finger hand on the same robot end effector. The first obvious solution is to have a dual end effector [1] with a finger gripper at one end and a suction cup at the other. However, this simple solution requires to buy two separate grippers which increases cost, weight and drives away center of mass, reducing the payload's weight. Also, a dual end effector is bulkier; when picking an object with a gripper, the other could collide with the environment.

In [2] the hand combines fingers and suction cup in the same mechanism. Soft wire driven fingers with three phalanxes are used for finger grasping. Suction cups are embedded into each of the finger's phalanxes, ensuring contact of the suction cup with the object when the fingers are closing on the object. This hand is capable of picking a wide variety of objects with three grasping methods, but the soft fingers and wire drive may not provide enough precision for assembly lines where positioning of the object is required or when force control is required to insert the object in its assembly. Moreover, having suction cups on each finger may prove unnecessarily complex and expensive in most industrial applications.

A different approach, as seen in [3, 4] consists in mounting the suction cup on the side of a finger hand, thus allowing independent grasping method but not combined grasping. The suction cup of [4] is mounted on a mechanism that allows it to extend beyond the finger tips which is good to reach objects in the corner of a box, for example. The distal phalanxes of the fingers remain parallel to each other while closing and opening. This characteristic will be referred to as parallel grasping. Parallel grasping allows for precise and robust grasping of objects. This hand is able to pick a wide variety of objects, but there are a few characteristics that may be improved. The distance from the robot end to the finger tips is long. This distance can be a nuisance because a small orientation error at the end effector causes large position errors at the finger tips; because, conversely, a small reorientation of the end effector may require large joint displacements. Another potential drawback is that the fingers cannot secure the grip on the object while the suction cup is holding it. Having two different actuators for the finger's and suction cup movement also increases the weight and cost of the hand. An interesting variant would be to mount the suction cup in between the fingers to achieve combined grasping.

This variant has been explored in a few different ways in references [5–7], where each of these three hands has rigid fingers for grasping and a suction cup mounted in its palm. The hand described in reference [5] uses two fingers with three phalanxes capable of parallel grasping, independent finger actuation and distal phalanx orientation adjustment. The mechanism includes underactuation between the finger's phalanxes: if an object touches the proximal phalanx before the distal phalanx, the finger wraps around the object, securing the grasp. With its many finger configurations, this hand can pick a wide variety of objects without resorting to its suction cup. The suction cup is mounted in between the fingers on a slider that extends beyond the finger's reach. The operating range of the proximal phalanx is 90° going from a horizontal position to a vertical position. While fully open, the fingers are very bulky and could prevent the robot arm from entering a box, for example. We refer to the space occupied by fully opened fingers will as the envelope, this envelope (red) and the robot arm (green) are represented in Fig. 1. The ideal robot hand would have no envelope allowing the robot to fully enter a box, bin or shelf without worrying about finger interference. For example, the gripper in Fig. 1(a) has a wide envelope compared to the robot arm, this wide envelope may prevent the robot from entering a box. However, a hypothetical gripper that has an envelope



(a) (b)

Fig. 1. Finger envelope in red and robot arm in green, (a) large envelope, (b) an ideal small narrow envelope

as shown in Fig. 1(b) would be able to enter a box without collision.

Lastly, some companies have developed their own hybrid hands [8, 9]. These two hands each have a suction cup mounted on a linear axis and independently-actuated fingers to secure the grip on the object. They present characteristics similar to those of the hands presented above [5–7]. However, their design is developed to the level of a consumer product, beyond the prototype level.

1.3. Problem definition

Drawing from the observation of all these grippers, some objectives and criteria are established to guide the design of the gripper in this research. Mounting the suction cup in between the fingers seems the best place to facilitate a combined grasp involving the fingers and the suction cup. First, the fully opened finger's envelope should be narrow and close the the robot arm as seen in Fig. 1(b). Second, the hand should be short and lightweight to increases agility and the net payload of the robot arm. Third, the finger's distal phalanxes should have a parallel trajectory to allow for pinching grasps, which are common in assembly applications. Fourth, only one actuator is to be used for the control of the fingers and suction cup to reduce cost and weight. With all these criteria, the gripper could be used in a wide variety of applications such as the pick and place of various objects with the combined use of the fingers and suction cup. Independent use of the fingers or the suction cup would make the gripper a two-in-one end effector, allowing one robot to accomplish two different types of tasks without changing the end effector. Food production could also benefit from this gripper because harvesting fruits requires delicacy that the suction cup can provide while the strength of the fingers required to detach the fruit from its plant.

1.4. Outline of the article

In this study we develop a single-actuator adaptive gripper with an integrated suction cup, that fits the requirements established by an examination of previous finger-suction-cup hybrid grippers. First, three concepts based on different architectures are presented. Second, the best concept is developed into a prototype. Finally, the solution is qualitatively evaluated based on the established criteria and then quantitatively evaluated with respect to the grasp strength, the grasp speed and envelope.

2. CONCEPT GENERATION

The first criterion to be addressed is the envelope around the robot arm. An ideal trajectory of the distal phalanx is defined in Fig. 2 around the robot arm and suction cup. If this trajectory is followed, the developed concept will satisfy the first (parallel grasping) and third (small envelope) criteria defined in section 1.3.

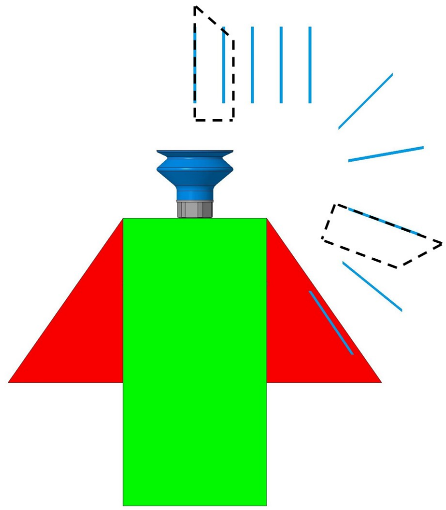


Fig. 2. Distal phalanx desired trajectory in blue

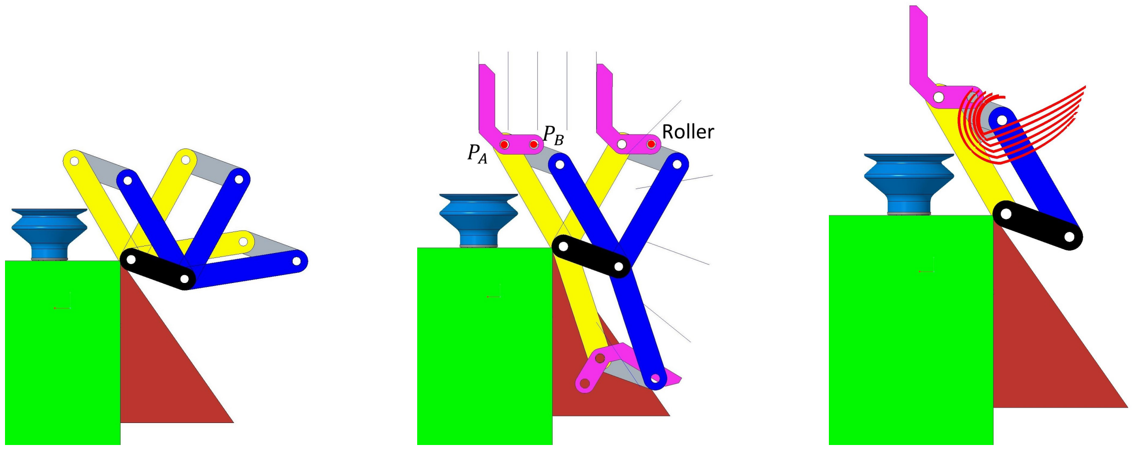
In order to generate this trajectory, we review three possible mechanisms. The first concept uses a cam to guide the phalanx orientation. The second concept is based on a four-bar linkage, which is synthesized through a path generation method. The third and last concept is an improvement of the second concept with more features.

2.1. Cam-based concept

This concept starts with a four-bar linkage to transmit the motion from the motor to the distal phalanx. In a parallelogram linkage, the orientation of the coupler does not change with the rotation of the input and output links. This characteristic is useful when designing a mechanism because this moving bar with a constant orientation can be used as a distal phalanx to achieve parallel motion.

The first step is thus to add parallelogram linkages around the robot arm and a suction cup to have a good idea of link length and possible pivot point. A pivoting distal phalanx, in pink on Fig. 3(b), is then added to the coupler link. The goal behind this is to orient the pivoting distal phalanx with a cam profile attached to one of the rotating links. To generate the cam profile, an analysis is made in CAD package Creo 5.0. A virtual position control is applied to the distal phalanx so as to guide it through the prescribed trajectory. This control keeps the distal phalanx vertical above the suction cup where grasping is done. After this vertical orientation, the distal phalanx starts to rotate clockwise to reach the envelope in red as shown in Fig. 3(b). Another position control is applied to the blue bar as shown in Fig. 3 so that it rotates between 120° and -70° relative to the horizontal. The cam profile spline is obtained by drawing the position of a lever on the distal phalanx relative to the blue output link, to which the cam is rigidly attached. Using different lengths between P_A and P_B, multiple cam profiles are drawn in Fig. 3(b). Thus, a cam profile is obtained and a 3D printed model is made for fast and low cost prototyping.

This concept satisfies the four criteria established previously, but in practice has some flaws that would need to be addressed for better performance. The cam and follower being an external surface joint, it is complex to keep the cam follower on the cam with a strong force. For this prototype the contact was obtained using a rubber band or small spring. The mechanism also has a singular position where the distal phalanx can branch into unwanted orientations. In fully opened position, the cam and the four-bar mechanism is narrow and very close to the robot arm. However, the cam is bulky and occupies much space in closed



(a) (b) (c)

Fig. 3. Cam development process

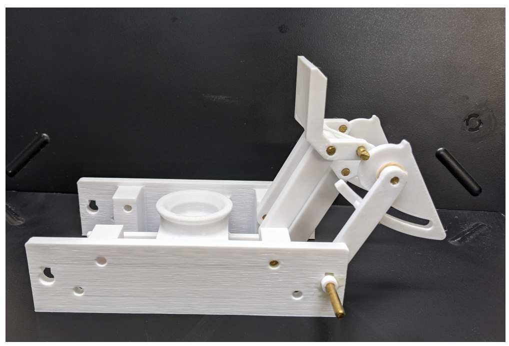


Fig. 4. 3D Printed prototype of the cam based concept

position, which may be a nuisance when picking objects from a box or bin.

2.2. Four-bar linkage concept

This next concept comes as the solution of a non-parallelogram four-bar path synthesis method known as "Burmester Problem" [10]. The method of solution used is explained and found in this book [11] section 3.4. This method was chosen here because it is possible to construct a linkage obtained through the predefined fixed pivots. Construction constraints are programmed in Creo and the four-bar mechanism is built from these constraints. It is therefore easy to change the location of the fixed pivots and instantly obtain the new mechanism corresponding to these pivots. Three precision poses of the distal phalanx are chosen as shown in Fig. 2, and used as input for the resolution method. This method returns a single solution to the input values, but the input values can be easily modified to obtain a different solution. The given solution is always a four-bar linkage guiding its coupler link through each precision pose. One of the drawbacks of this method is that the path between these poses is generally convoluted making the mechanism impractical.

First, fixed pivot are chosen by the user, in this case we chose points near the robot and below the lip of the suction cup because these pivots will not move and could interfere with the object if they were placed far from the robot or above the lip of the suction cup. The fixed pivot are P_1 and P_2 shown in Fig. 5. Second, a triangle is drawn between P_1, the base and the end of the third phalanx pose. This triangle is then replicated with the exact same dimension onto the first phalanx pose, the location of P_3 will be used later. Third, the same process defined in second is done this time using the second phalanx pose which returns P_4. Fourth, a circle passing through P_1, P_3 and P_4 is drawned, the center of this circle, P_5, is the first mobile pivot of the four-bar linkage. Fifth, second and third step are repeated using the fixed pivot P_2 which returns P_6 as the second mobile pivot of the linkage. Knowing the position of P_1, P_2, P_5 and P_6 the four-bar linkage shown in Fig. 6(a) can be drawn.

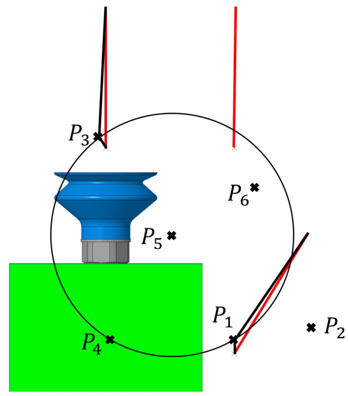
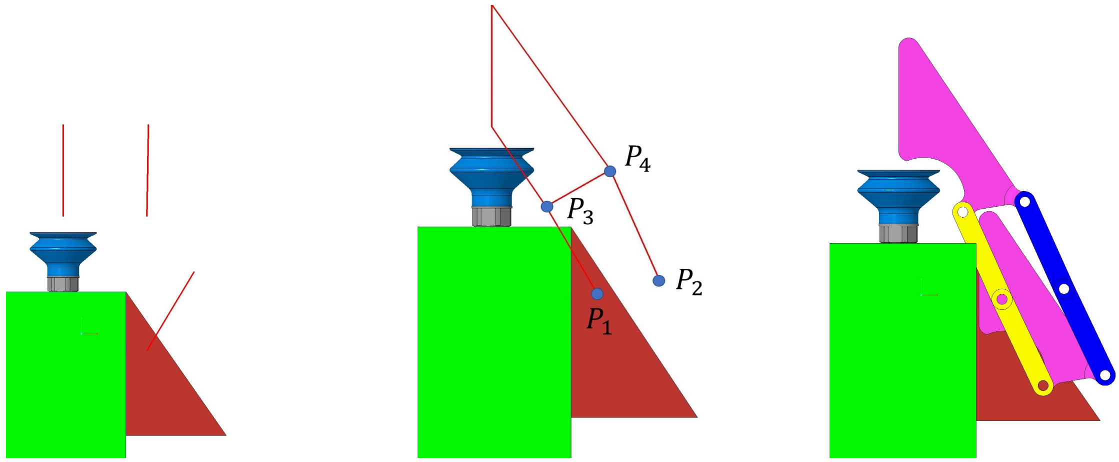


Fig. 5. Four-bars linkage systhesis method mobile pivots constructions

Many attempts were made to find a proper four-bar linkage that satisfies the criteria for this study. The three distal phalanx poses shown in Fig. 6(a) were selected because they gave one of the most promising mechanisms obtained by this method represented in Fig. 6(b). The motion through the three poses is not quite fluid nor parallel so the third criterion for parallel grasping is not satisfied. Also, the fully open position of the finger is not contained in the desired envelope in red on Fig. 6(b). From these results, the conclusion made is that the path synthesis method points towards a parallel four-bar linkage for the chosen poses. To make the mechanism more reliable and stable, it is then approximated as shown in Fig. 6(c) i.e., as a parallelogram. This mechanism has a connecting rod on the coupler link which is the distal phalanx. The shape of this bar can be modified in order to meet more constraints without modifying the operation of the mechanism. The mechanism is therefore adapted to avoid collisions between the connecting rod and the suction cup or the robot. In fully open position, it is about half contained in the ideal envelope around the robot arm, as shown in Fig. 6(c) which is good for grasping objects in boxes or bins.



(a) (b) (c)

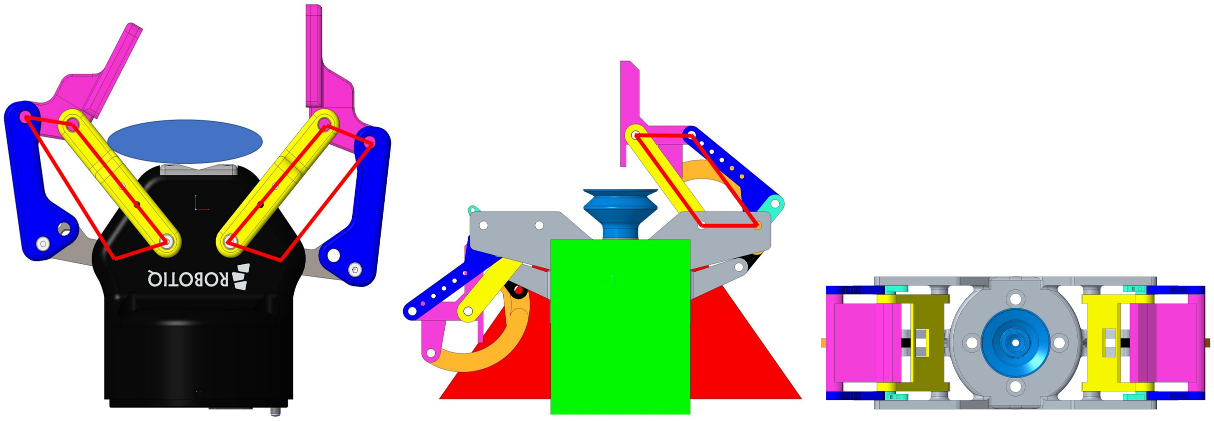
Fig. 6. (a) distal phalanx three input positions, (b) four bars mechanism generated, (c) adapted mechanism

This concept was developed by following the method of [11], but turns out to be close to a well-known solution, the parallelogram linkage. This latter solution shown in Fig. 6(c), has good characteristics such as parallel grasping and a small envelope. The next concept improves upon this mechanical design to satisfy all design constraints.

2.3. Parallel four-bar linkage concept

After some research, we found that the gripper originally proposed in [12] and commercialised by Robotiq [13] has interesting features such as parallel grasping and compliant grasping. As described in section 1.2, if an object touches the proximal phalanx before the distal phalanx, the distal phalanx will wrap itself around the object. This characteristic comes from the architecture of the finger, as shown in red on Fig. 7(a), where the pivot of the driving link, proximal phalanx and the distal phalanx form a parallelogram mechanism. These four bars keep the distal phalanxes vertical when no contact is made. When contact is made on the proximal phalanx in yellow, the driving link in grey continues to rotate, thus making the left four-bar linkage non-parallel as shown in Fig. 7(a). When this occurs, the orientation of the distal phalanx is changed to wrap around the object, the underactuation mechanism is found in references [12, 14]. The finger architecture is reused in the concept presented in this section as shown in Fig. 7(b). This gripper has a two-finger design, actuated by only one motor, that would accommodate a suction cup. The driving link of the finger, represented in grey on Fig. 7(a), has a stroke of 45° which is not enough for our purpose. Indeed, this prevents the fingers from opening widely, and the suction cup positioned in between the fingers from picking a flat object, e.g. a credit card on a table.

The concept in this section aims to adapt the gripper of Robotiq to integrate a suction cup and to increase the abduction angle of the fingers so that the gripper has a smaller envelope. The abduction range of approximately 45° is limited by the actuation stroke and by the interference of the different parts of the fingers during rotation. To begin the design, the limitation of the actuation stroke is neglected and will adressed later on, the primary focus being set on the interference of the rotating parts. In the gripper of Robotiq, the distal phalanx, proximal phalanx and driving link are all positioned on the same plane. If the driving link were to rotate without limit, it would collide with the phalanxes and stop the motion. This problem is solved by staging the moving parts on different planes, thus expanding the rotation stroke. To achieve this staging, the connecting rod in blue on Fig. 7(a) has been duplicated and placed on two parallel planes on both sides of the distal phalanx as shown in Fig. 7(c). With these modifications the finger can rotate freely from the mid



(a) (b) (c)

Fig. 7. (a) Fully opened Robotiq 2F-85 gripper with the left finger in compliant grasping and right finger parallel grasping, (b) Concept gripper with the left finger in open position and the right finger in closed position, (c) Top view of the concept gripper

plane of the suction cup to the retracted position close to the ideal envelope shown in Fig. 7(b). A simple four-bar linkage with a fixed bar such as the four bars presented in Fig. 7(b) has a singularity that needs to be eliminated for a controlled motion of the fingers. In rotation when the two long bars intersect each other, the linkage has two possible assembly positions; one is the parallelogram and the other is an X shape, we need to preserve the parallelogram shape as the parallelogram moves through its singular flat configuration. To this end, the orange bar in Fig. 8 is added to the finger to act as a second parallelogram that keeps the shape of the first parallelogram. This idea has been used in trains for decades, to couple the rotations of multiple wheels while avoiding singularities.

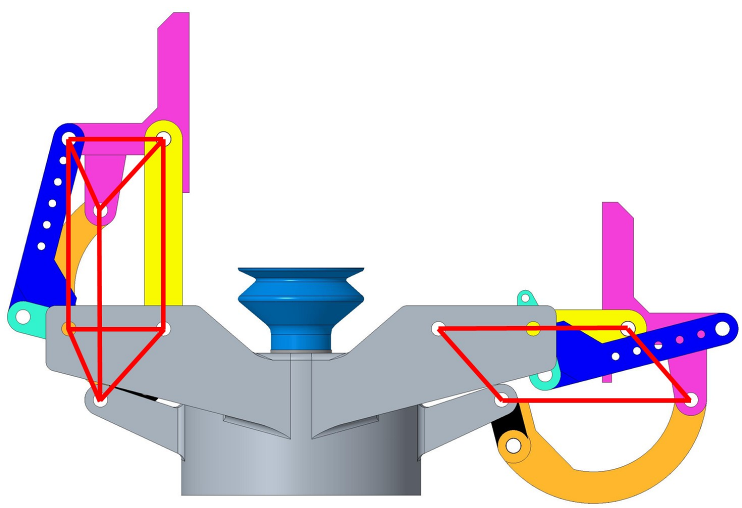
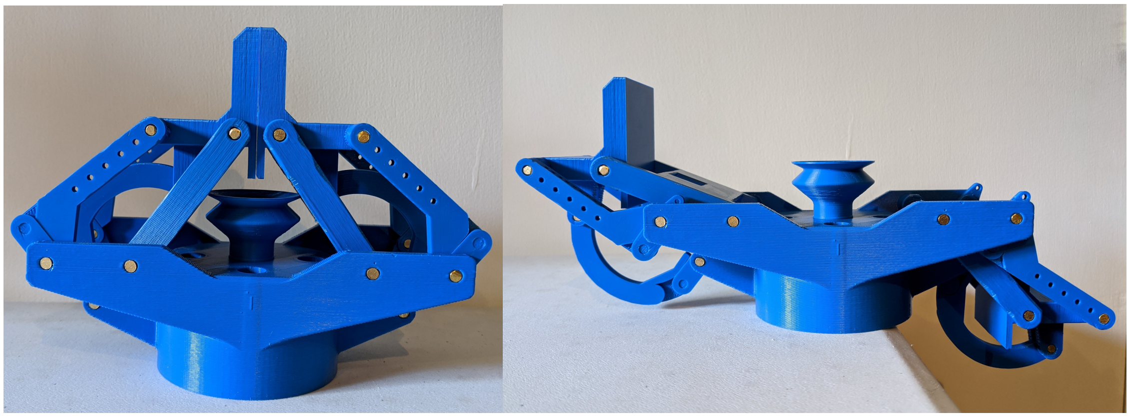


Fig. 8. Cad model of the concept with a demonstration of a double parallelogram linkage for redundancy

A prototype of the mechanism shown in Fig. 10 is made to test the fingers motion and to identify any singularity or interference. The prototype is 3D printed because this process is fast and inexpensive. The fingers are hand powered, there being no motor attached to them. The results are conclusive, the mechanism indeed follows the desired trajectory without encountering singularities. Clearances in the pivots can cause the fingers to block but this can be fixed with proper fits and tolerances. This prototype has demonstrated the functionality of this mechanism, but there is still room for improvements in tolerances, finger dimensioning and actuation. These are discussed in the next section.



(a) (b)

Fig. 9. Prototype in different positions, (a) closed, (b) left finger half opened and right finger fully opened

The proposed prototype has a complex finger mechanism but with regards to the evaluation criterion is an appropriate solution. The mechanism allows the fingers to open widely enough to clear the plane of the suction cup. With this plane free, the suction cup can be fixed in the palm of the hand without the need for a linear axis to extend the suction cup. This results in a shorter and lighter gripper.

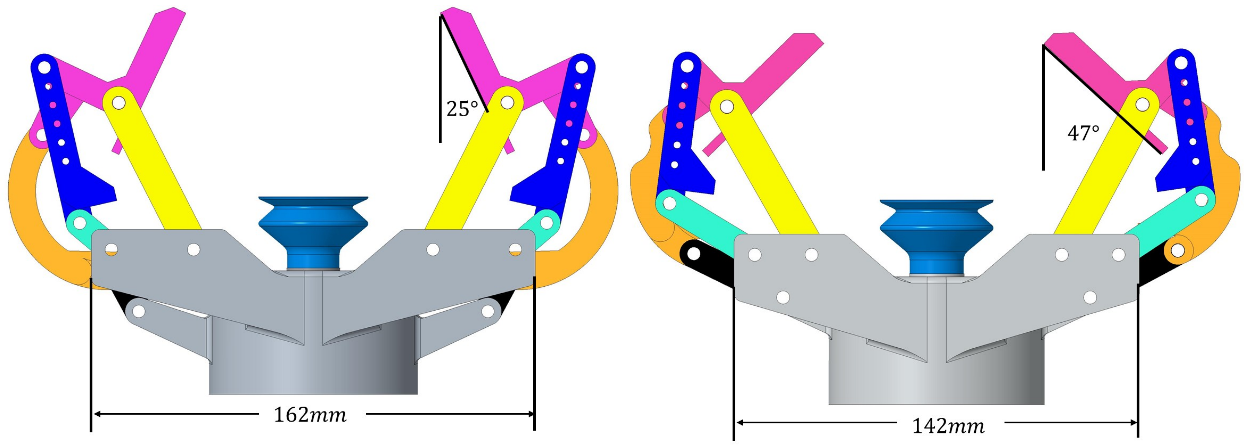
3. ACTUATED PROTOTYPE

In this section, the hand-powered prototype of section 2.3 is improved and adapted into an actuated prototype. The main objective of this prototype is to test the fingers and suction cup grasps on real objects. Therefore, the components for the motor and the drive train we selected because of their availability and prices to make a low-cost functional prototype.

Before making the prototype, modifications are made to the dimensions of the fingers. In the previous prototype, the complient grasp of the distal phalanxes was about 25° inwards. With small adjustment of the linkage lengths, it is modified to expand the compliant grasp range to 47° shown in Fig. 10(b). The width of the base is also reduced by 20mm to reduce the footprint of the mechanism.

A DC servo motor is selected to drive the system for the following reasons: its control is simple; it includes a reducer in a compact casing; there are many different torques and strokes to choose from; and it is inexpensive. To simplify calculations, the four-bar linkage is reduced to a single link with the torque of the motor applied to it. Because the linkage is a parallelogram, the orientation of the distal phalanx remains vertical at any given angle θ, as shown in Fig. 11(a). The torque T applied to the proximal phalanx results in a force applied to the distal phalanx. The position and direction of F are given by P, F is perpendicular to P. F is then calculated using the vector norm of P as shown in eq. 1 where T is half the stall torque of the motor, there being two fingers to drive. The grasp strength of the gripper is F_x which can be calculated through F as shown in eq. 2. Relations are then made between the parameters to express F_x in terms of x. The grip strength at the tip of the fingers shown in Fig. 11(b) is obtained with a 3.43 N m stall torque DC servo motor.

$$F = \frac{T}{\|\vec{P}\|} = \frac{T}{\|(e\cos\theta)\hat{x} + (e\sin\theta + d)\hat{y}\|} \tag{1}$$



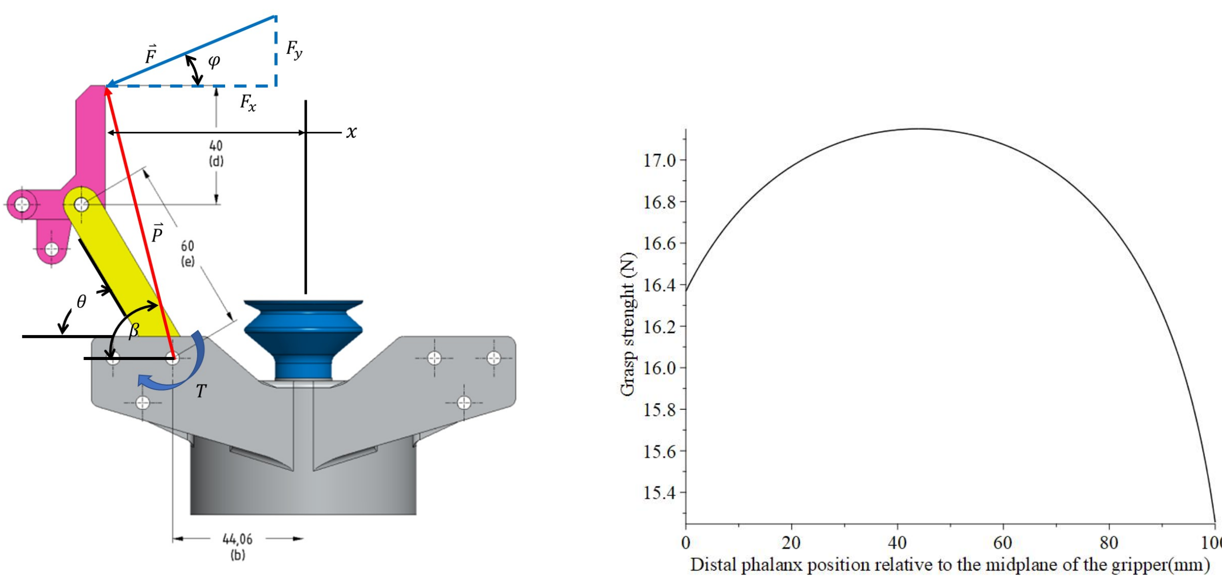
(a) (b)

Fig. 10. Prototype optimization for compliant grasp and general width (a) Before, (b) After

$$F_x = F\cos\phi \tag{2}$$

$$\theta = \arccos\left(\frac{x-b}{e}\right) \tag{3}$$

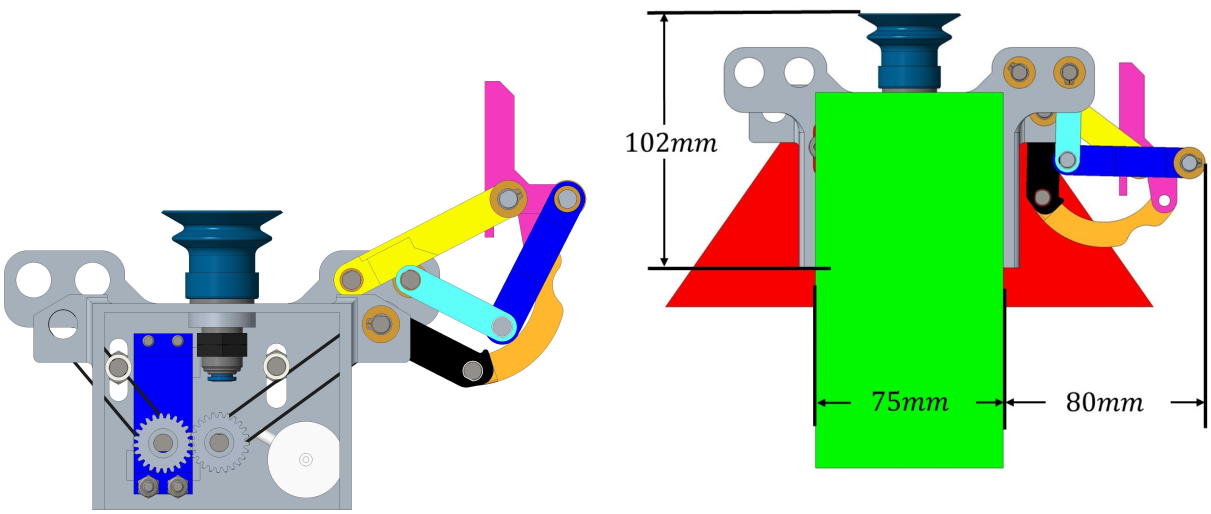
$$\phi = \frac{\pi}{2} - \beta = \frac{\pi}{2} - \arctan\frac{P_y}{P_x} \tag{4}$$



(a) (b)

Fig. 11. (a) Forces diagram, (b) Grasp strength of the prototype

The torque of the motor is transmitted to the drive link using gears and timing belts. The drive link is the black link shown in Fig. 12(a). A torsion spring is located between the black and orange links to force the orange link counterclockwise for the right finger. This spring keeps the underactuation mechanism from moving, otherwise the distal phalanx would not keep a vertical orientation when no contact is made on the yellow proximal phalanx. An air pump, shown in white, is placed inside the base of the gripper, the pump needs a power supply of 6V 1.2A to make a vacuum of −60kPa at 3.2L/min. This pump was chosen for its light weight, compact format and low cost with the intention of making a functional gripper. This embedded pump generates vacuum in the suction cup without the use of an external air compressor hence removing the need for an air supply line to the gripper. For better performance of the suction cup grasp, an air pump with better specifications should be used, the vacuum gripper of reference [15] has a pressure of −80% atmospheric pressure at 12L/min. This prototype is currently in fabrication and will be tested on a robot eventually.



(a) (b)

Fig. 12. (a) Actuated prototype design, (b) Gripper outside dimensions

4. EVALUATION OF THE ACTUATED PROTOTYPE

The actuated prototype being in fabrication, a qualitative assessment is made based on the criteria established in section 1.3. First, the fully opened fingers should have the smallest possible envelope. The opened finger shown on Fig. 12(b) exceeds the ideal envelope in red, but this still represents a marked improvement over the original design in [12]. The linkage of the fingers was developed with the intent to make the fully open finger as close as possible to the robot arm. With a total width of 235mm we consider this criterion to be satisfied. Second, the gripper should be short and lightweight, which is the case with a gripper height of 102mm and only one actuator for minimum weight. The fixed suction cup saves weight and height compared to those mounted on linear axes which were proposed in references [5–7]. Third, the distal phalanxes should remain parallel while closing the grasp which is the case. Fourth, the gripper should have a single actuator, a constraint that is also satisfied.

5. CONCLUSION

The objective of this research was to combine the finger grasping and vacuum grasping technologies. Three concepts were explored: a cam-based concept, a four-bar linkage concept and a parallel linkage. The first concept had an interesting feature such as a small envelope in the opened position but had a large envelope in closed position. The second concept also had a small envelope but lacked parallel grasping. The third concept has both a small envelope in closed and opened position, parallel grasping, compliant grasping and a single actuator. The fixed suction cup does not need an actuator and saves weight and height of the gripper. These benefits have a drawback however; if an object is positioned in the corner of a shelf, bin or box, even with the small envelope of the gripper, it could be difficult to reach the object with the suction cup. The alleviation of this drawback is the subject of future research.

6. ACKNOWLEDGMENT

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