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Design and analysis of a novel light-weight, linear actuator driven flexible PET strips robotic gripper

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Abstract: A robotic manipulator consists of a robotic arm and an end-effector. The function of the end-effector or robotic gripper is to allow the robotic arm to grasp and manipulate objects. The traditional hard robotic grippers are prone to poor gripping ability when grasping objects with irregular shape or in-ability to passively adjust force to delicate objects. Soft Robotic grippers were purposely designed to solve these disadvantages. In this work, a novel light weight robotic gripper based on grasping action of holding an object in between two strips of in-elastic flexible material under tensile force developed when pulled is hereby presented. Force analysis of the gripper was carried out as well as validation experiments. Analysis shows that the minimum pulling force to be exerted by the gripper on the grasping strips is directly proportional to the payload mass and the strips lengths. It is also inversely proportional to the coefficient of static friction between the payload-strips interface and the horizontal extent of the payload. Experimental results supported these observations. Moreover the predicted analytical values of gripper pulling force agreed reasonably with the empirically derived values. A proof of concept model of the gripper successfully grasps a 185g object.

Keywords: PET plastic strips, robotic gripper, linear actuator, end-effector.

I. Introduction

The robotic arm, which is a type of programmable mechanical manipulator similar in functions to human arm usually have attached to its "Wrist" end a device commonly referred to as 'End-effector'. This is the part of the robot that carries out the desired task of the robotic arm [1]. The end-effectors may be grouped into two; grippers or tools. The gripper manipulates objects (payload) similar to one or more ways a human hand can manipulate an object. Simple grippers are designed to hold and release objects while the more dexterous ones can go further in their abilities to pinch, roll and rotate object between fingers. Some are provided with tactile sensors which provides feedback to the controlling computer while others are programmed in terms of the magnitude of tactile force they can applied to object. The core requirements of a robotic gripper are ability to grasp broad range of geometries, safety in use, adaptability, simplicity and affordability [2]. Anthropometric grippers mimic human hand in their topology while non-anthropometric grippers has very little or no resemblance to human hand. In general,

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grippers are broadly categorised into two: Soft robotic grippers and hard robotic grippers [3]. Hard (or traditional) robotic grippers consist of rigid links and joints [2] and perform well in grasping objects with a well-defined geometry and compliance. Their main drawbacks are poor gripping ability when grasping objects with irregular shape or in-ability to passively adjust force to delicate objects. Moreover, their rigid surfaces and incompliant interaction with objects makes hard grippers tends to deform or even destroy fragile payloads [4]. Soft robotic grippers were purposely designed to solve this disadvantage inherent in rigid robotic grippers. There are varieties of soft robotic grippers that had been developed with each having a uniqueness of its own, depending on how grasping is to be achieved [3-8] with each having its own weaknesses and strengths. Trends from literature shows that more novel designs of robotic grippers are a possibility and unique varieties are still coming. These will provide in the long run a pool of robotic gripper solutions to robotic grasping problems from which industries can choose and adapt to their unique needs and requirements.

In this work, a novel light weight gripper based on grasping action of holding an object in between two strips of in-elastic flexible material under tensile force is hereby presented. The robotic gripper was designed to be light weight, affordable, easy to assemble, disassemble, and having mechanically minimal number of components. The gripper has ability to hold payload in passive (non-powered) mode, it only requires power when picking and releasing objects. It was intended to have broad applications in industries where pick and place robotic function is required in their automated production systems.

II. Materials and Methods

A. The Concept

The design procedure follows the general machine design format as laid out by [9]. The idea for the gripping action of the robotic gripper is as depicted graphically in Figure 1a. The two PET (Polyethylene Terephthalate) strips in parallel hold the object in between them when the strip anchor is under the pulling forces P. This action leads to a reaction force at the object-strip interface. This in turn generates frictional forces which will prevent the object from sliding down under its own weight W. With the strips held tight on the object due to pulling forces P, the griper attached to a robotic arm can then manipulate the object as long as the magnitude of the weight does not exceed the generated frictional forces. The choice of PET as strip material was due to its good physical and mechanical properties, as well as good dimensional stability under variable load [10].

B. Force analysis

Referring to Figures 1b and 1c which gives the gripper concept in plan and elevated views, let the pulling force on the PET strips be P (N), T is the tension in the strips (N), W is the weight (N) of the object; f is the fictional force (N) between the object and one of the PET strips, and η is the normal reaction (N) of the object due to the tightening effect of the strips under the effect of pulling forces. The object was modeled as a cylinder (in practice it can be of any shape) with radius r (m), a and b are angles in degrees. Resolving forces at point A along x axis and assuming the strips are inelastic;

$P - 2T Cos\ a = 0$ (Equilibrium condition) ..(1)

$$T = \frac{P}{2Cos\ a} \quad \ldots \quad \ldots\ldots \quad \ldots \quad (2)$$

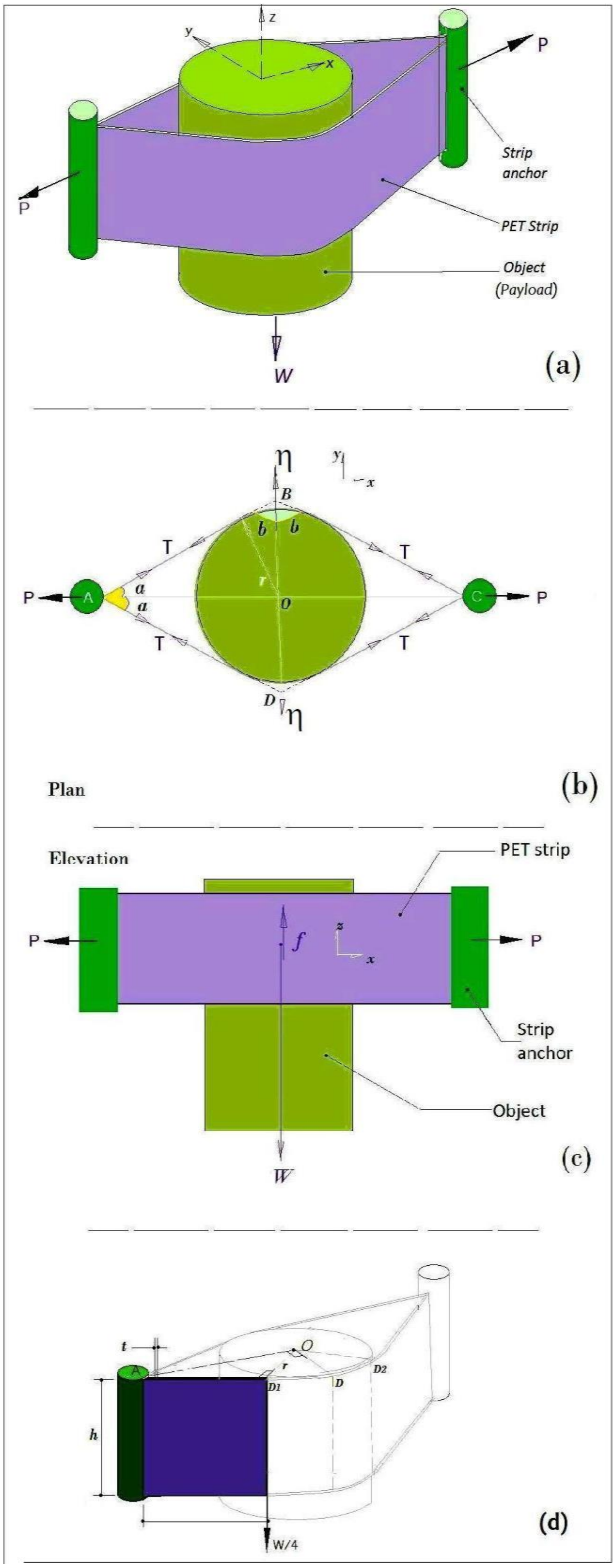


Figure 1: Conceptual (a) and force analysis diagrams (b-d)

Resolving forces at point B along y axis:

$$\eta - 2T\cos b = 0 \quad \text{(Equilibrium condition)} \quad \ldots \quad (3)$$

$$T = \frac{\eta}{2\cos b} \quad \ldots \quad (4)$$

Combining Equations (2) and (4);

$$P = \eta\left(\frac{\cos a}{\cos b}\right) \quad \ldots \quad (5)$$

In the elevation diagram in Figure 1c, resolving forces along the vertical (z axis) direction;

$$2f - W = 0 \text{(Equilibrium condition)} \quad \ldots \quad (6)$$

For the gripper to be effective in object grasping, $2f \geq W$. Hence the minimum frictional force required to hold the object in grip is $2f = W$. But;

$$f = \mu\eta \quad \ldots \quad (7)$$

where μ is the coefficient of static friction between the PET strips and the object.

$$W = 2\mu\eta \quad \ldots \quad (8)$$

$$mg_o = 2\mu\eta \quad \ldots \quad (9)$$

Where m is the mass (kg) of the object and g_o is the acceleration (ms^{-2}) which can be further decomposed into ($g + \alpha$) where g is acceleration due to gravity and α is the acceleration due to the movement of the robotic arm when the payload is being manipulated. When the gripper is grasping the payload without any movement by the robotic arm to which it was attached, $g_o = g$. Substituting for η in Equation (5);

$$P = \left(\frac{mg_o}{2\mu}\right)\left(\frac{\cos a}{\cos b}\right) \quad \ldots \quad (10)$$

From geometry in Figure 1b;

$$\left(\frac{\cos a}{\cos b}\right) = \frac{/OA/}{/OB/} \quad \ldots \quad (11)$$

Let q be the distance between the two anchors when the objects had been gripped (corresponding to /OA/), and S corresponding to /OB/, then;

$$\frac{/OA/}{/OB/} = \frac{q}{s} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots(12)$$

Then Equation (9) became;

$$P = \left(\frac{mg_o}{2\mu}\right)\left(\frac{q}{s}\right) \quad \ldots\ldots \quad \ldots \quad \ldots(13)$$

Next, consider Figure 1d, the portion A-D1-D1'-A' may be consider as a cantilever under the load W/4, where W is the weight of the payload. The stress σ (N/m^2) induced in this segment due to the bending action of force W/4 is given by [2]:

$$\sigma = \frac{My}{I} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots(14)$$

Where M is the bending moment (Nm), *y* is distance (m) from the neutral axis, I is the Moment of inertia (m^4) of the cross-section about the neutral axis.

$$M = (W/4)(/A'DI'/) \ldots\ldots\ldots \quad \ldots \quad \ldots(15)$$

$$I = \frac{tb^3}{12} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots(16)$$

Where t is the PET Strip thickness, and b is the strip width, with y = b/2, then combining Equations (14) (15) and (16);

$$\sigma = \frac{3W\,/A'D1'/}{2tb^2} \quad \ldots \quad \ldots \quad \ldots \quad \ldots(17)$$

The implications of Equations (13) and (17) from design point of views are as follows:

(i)The pulling force on the gripper PET strips is directly proportional to the payload weight as well as lengths of the PET strips.

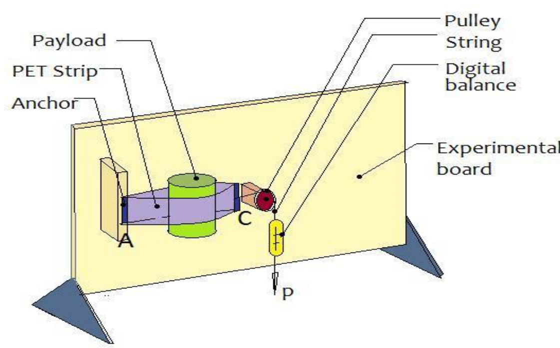
(ii) The pulling force is indirectly proportional to the coefficient of friction between the payload and the strips' surfaces as well as the physical width of the payload.

(iii) The stress induced in the strip by the payload due to the bending moment effect is directly proportional to the payload mass and the length of the PET strips and inversely proportional to the thickness and width of the strip.

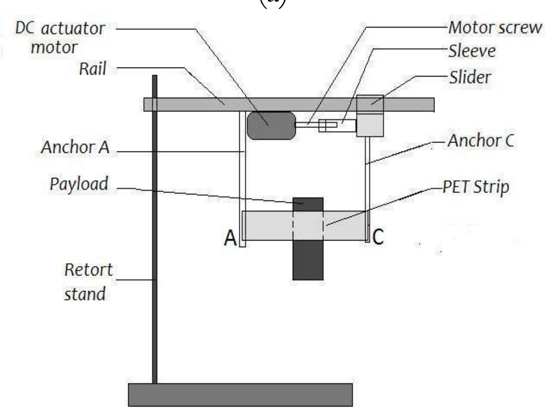
C. Experiments

Two sets of experiments were carried out to (i) validate the relationship of pulling force P with the payload weight W with respect to coefficient of static friction at the payload-PET strips interface and the physical horizontal extent of the payload; (ii) to demonstrate the proof of the concept as described in section IIA. The schematic of the experimental rigs were as depicted in Figure 2a and 2b respectively.

For analysis verification, a pair of plain PET strips of length 150mm, width 30mm and thickness 0.5mm were mounted on the rig anchors A and C as shown in Figure 2a.



(a)



(b)

Figure 2: Experimental set-ups (a) Variation of pulling force with payload mass, payload physical size and interface friction coefficients; (b) Proof of concept rig.

Two cylindrical PVC plastic containers of external radii 32mm and 50mm respectively, with identical height 70mm were used as the payload. The cylinders were filled in turn with known weights to attain different payload levels of 45, 65, 85 and 105g. At each level the cylinder was placed between the strips in the expected gripping pose of the gripper. Then anchor C was manually pulled via a string and push-pull gauge (Eleoption SF-500 Digital pull push gauge) until the payload is tightly secured by the strips. The tension in the string was then slowly reduced by gradually relaxing the manual pull until the container just start to slide down between the strips. The value of the minimum pulling force required to secure the payload as well as the payload mass was then recorded.

This procedure was repeated for the other payload mass levels. The procedure was duplicated for the two cylinders. Next, the inner surfaces of the PET strips loop were overlaid with very thin rubber strips of similar dimensions. This was done in order to increase the value of coefficient of friction between the payload and the strips. The previous procedures were then repeated for this new contact surfaces.

Finally, a DC Motor with screw spindle to mate with a hollow threaded sleeve was mounted (Figure 2b) on the rig in order to move anchor C coupled with the slider away from or towards the fixed anchor A thereby gripping or releasing the pay load. Four common objects of various masses and shape were placed in the gripper loop and the ability of the actuator motor to hold and release the objects were observed and reported.

III. Results and Discussion

The relationships between the payload weight and the minimum experimentally determined pulling force with respect to payload physical size and nature of the payload PET strips interface was as depicted in Figure 3a. As predicted by Equation (13), there is a linear relationship between the gripper pull (P) and the payload weight (W). The mathematical relationships for the empirically derived values for P and W for the payload range 0.45N to 1.05N was as shown in Equations (18)-(21)

$$P = 4.31W \quad (R^2 = 0.97) \qquad (18)$$

(Payload cylinder diameter 33mm, gripper plastic surface on payload plastic surface)

$$P = 1.69W \quad (R^2 = 0.92) \qquad (19)$$

(Payload cylinder diameter 33mm, gripper rubber surface on payload plastic surface)

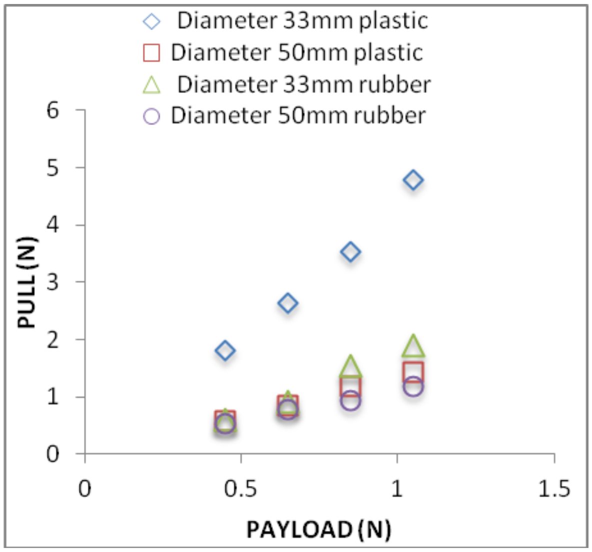
$$P = 1.35W \quad (R^2 = 0.99) \qquad (20)$$

(Payload cylinder diameter 50mm, gripper plastic surface on payload plastic surface)

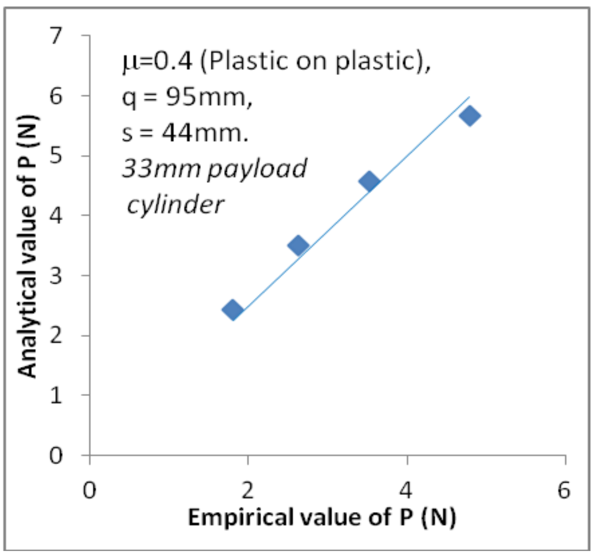
$$P = 1.13W \quad (R^2 = 0.99) \qquad (21)$$

(Payload cylinder diameter 50mm, gripper rubber surface on payload plastic surface)

These results shows that coefficients of friction between the payload/gripper interfaces as well as payload physical size and weight determines the magnitude of the minimum pull to be exerted by the gripper as previously shown analytically. From gripper design point of view, the gripper surface material may be regarded as a constant unlike the payload which is any object that can be geometrically accommodated by the gripper strips in-between them. The PET Strips themselves are not expected to be changed often. Thus the gripper strips should be inelastic, flexible material with surface having high coefficient of friction when in contact with



(a)



(b)

Figure 3: (a) Relationships between gripper pull and payload with respect to payload physical size (in cylinder diameter) and nature of the payload PET Strips interface (plastic indicates plastic-plastic interface; rubber indicates rubber (on PET strips)-plastic (payload external surface) interface. (b) Relationship between the analytical and empirical values of gripper pull for a particular set of parameter values.

most common daily items expected as its payload. The strips may be homogenous or made of composite materials in order to achieve the aforementioned properties.

Figure 3b shows the relationship between analytical values obtained for P using Equation (13) and the corresponding empirical values for the parameters indicated on the Figure. The mathematical relationship between the two for payload range 0.45N to 1.05N with μ taken as 0.4 for plastic on plastic [11] in the analytical process is:

$$P_A = 1.25P_E \quad (R^2 = 0.97) \ldots \quad \ldots \quad \ldots(22)$$

Where P_A and P_E are analytical and empirical values of P respectively. This expression indicates that the theoretical relationship (Equation 13) between the gripper pull and payload weight can reasonably predict the minimum pull necessary to grasp a particular payload.

The design approach used in this present robotic gripper was validated by constructing a prototype based on the experimental rig presented in Figure 2b. . The results obtained indicated that the end-effector can perform enveloping grasps for a variety of objects, passively adapts to the shape of the object while maintaining stable grasps and ability to hold onto payload even when there is power cut to the linear actuator. Figure 4 show the demonstration prototype holding some familiar objects. The maximum mass of payload observed as being successfully grasped and held by the proof of concept prototype was 185g. This is within the range reported for soft robotic grippers that adopted different design approaches but with similar physical sizes [6-8, 12-14]. It is of note that the payload carrying capacity of the demonstration prototype can be increased simply by overlaying the PET Strips

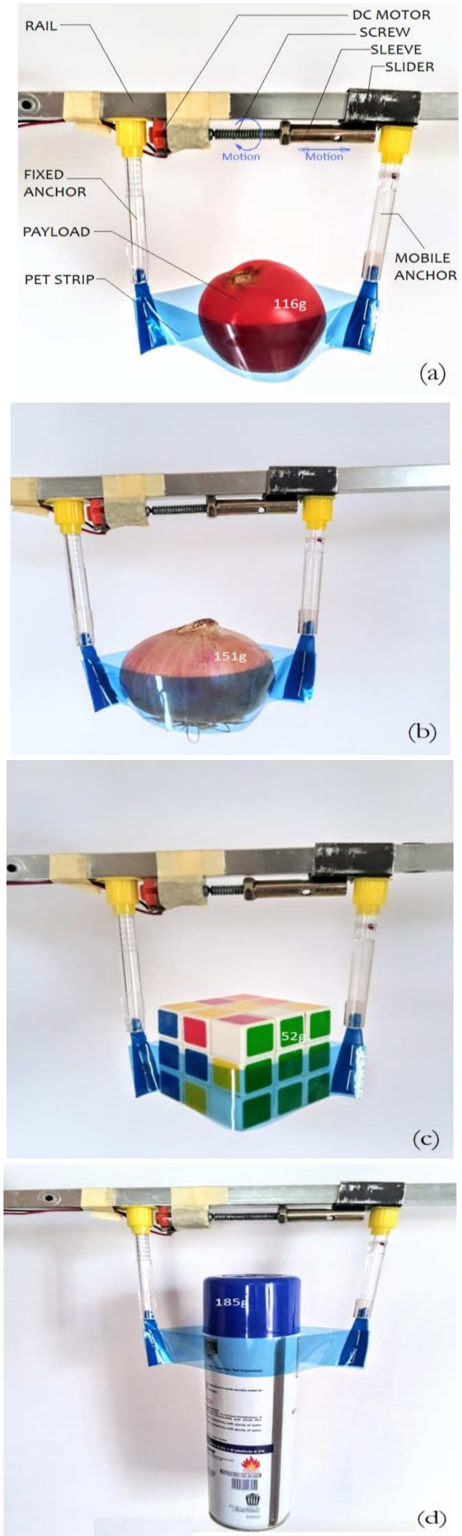


Figure 4: Test for grasping different objects with the robotic gripper: (a) tomato (116g) (b) onion (151g) (c) Rubik cube (52g) and (d) insecticide can (185g)

with material having higher coefficient of friction as observed in Figure 3a.

However, scaling up for a commercially feasible prototype, Figure 5 depicts a version intended for commercialization. The materials of fabrication (as indicated in the diagrams) are commercially available and relatively cost effective. Moreover, intended (geared) DC actuator motor is widely available commercially

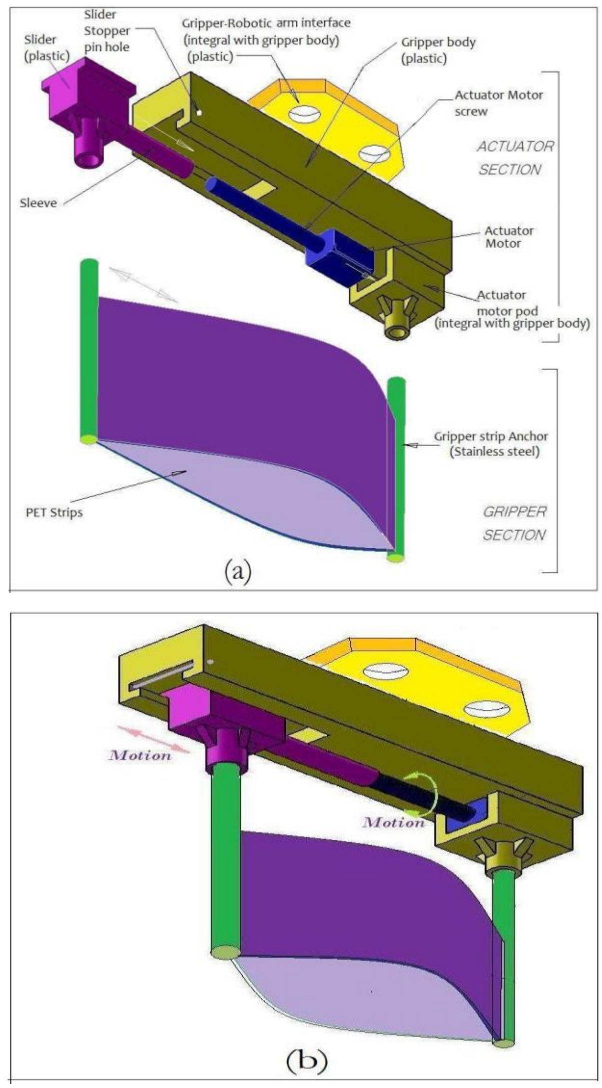


Figure 5: The *Solidwork* rendering of the conceptual commercial version of the robotic gripper (a) exploded view; (b) assembly perspective view

at relatively cheap price. Hence, coupled with the relatively few components the gripper incorporated and the minimal mechanical complexity, this will results into it ease of mass production. The design also has intrinsic scalability which ensures its production in various sizes depending on the type of payload it is intended for.

IV. Conclusion

This work successfully demonstrated the possibility of using the idea of grasping action of holding an object in between two strips of in-elastic flexible material under tensile force developed when pulled as a basis for the development of a novel robotic gripper. The minimum pull on the strips in order to grasp objects was analytically and empirically shown to be directly proportional to the payload mass and the strips lengths. It is also inversely proportional to the coefficient of static friction between the payload-strips interface and the horizontal extent of the payload. The robotic gripper demonstration prototype constructed successfully grasped a selected sample of familiar objects with the maximum mass of object grasped being 185g.

V. Acknowledgements

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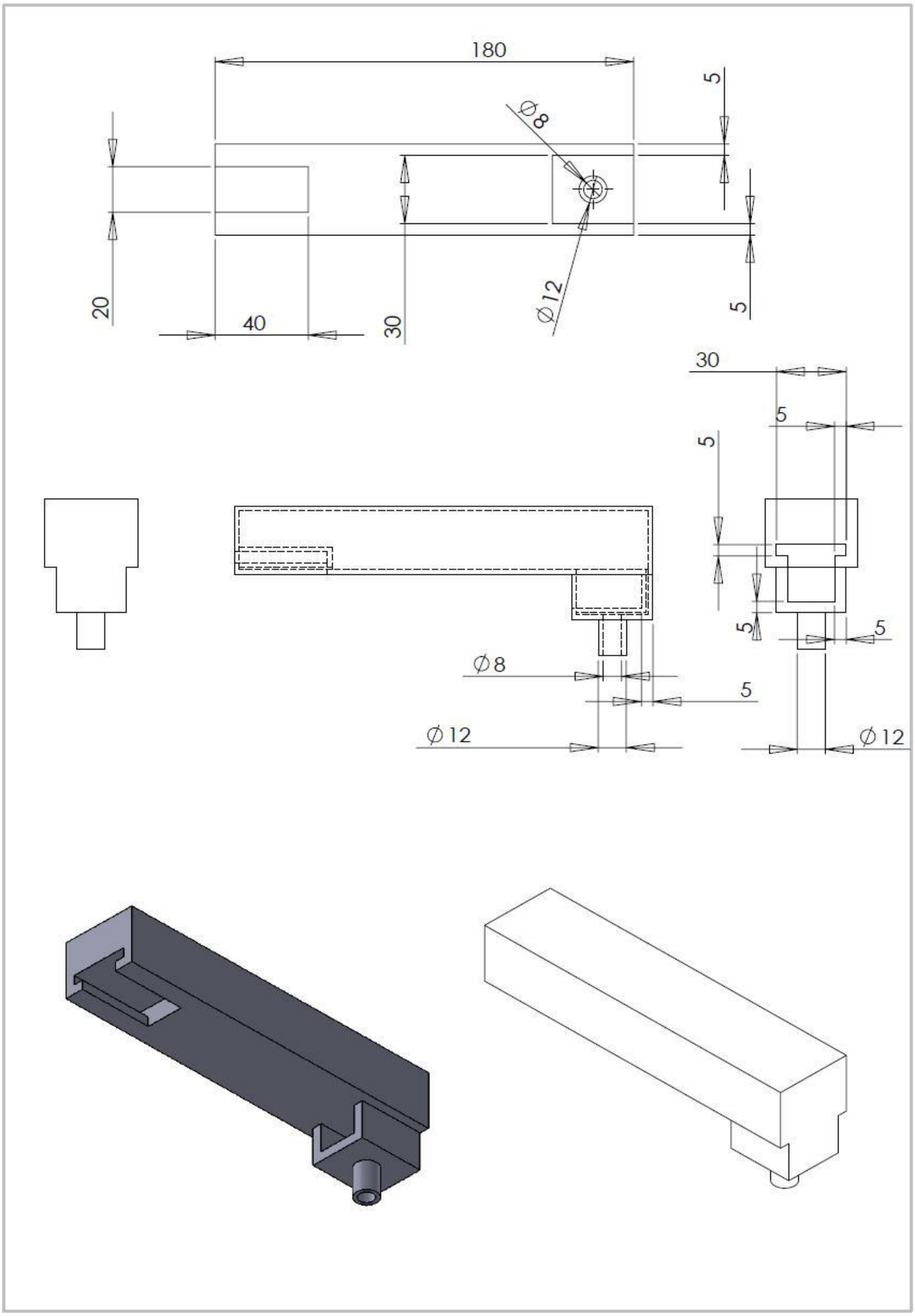
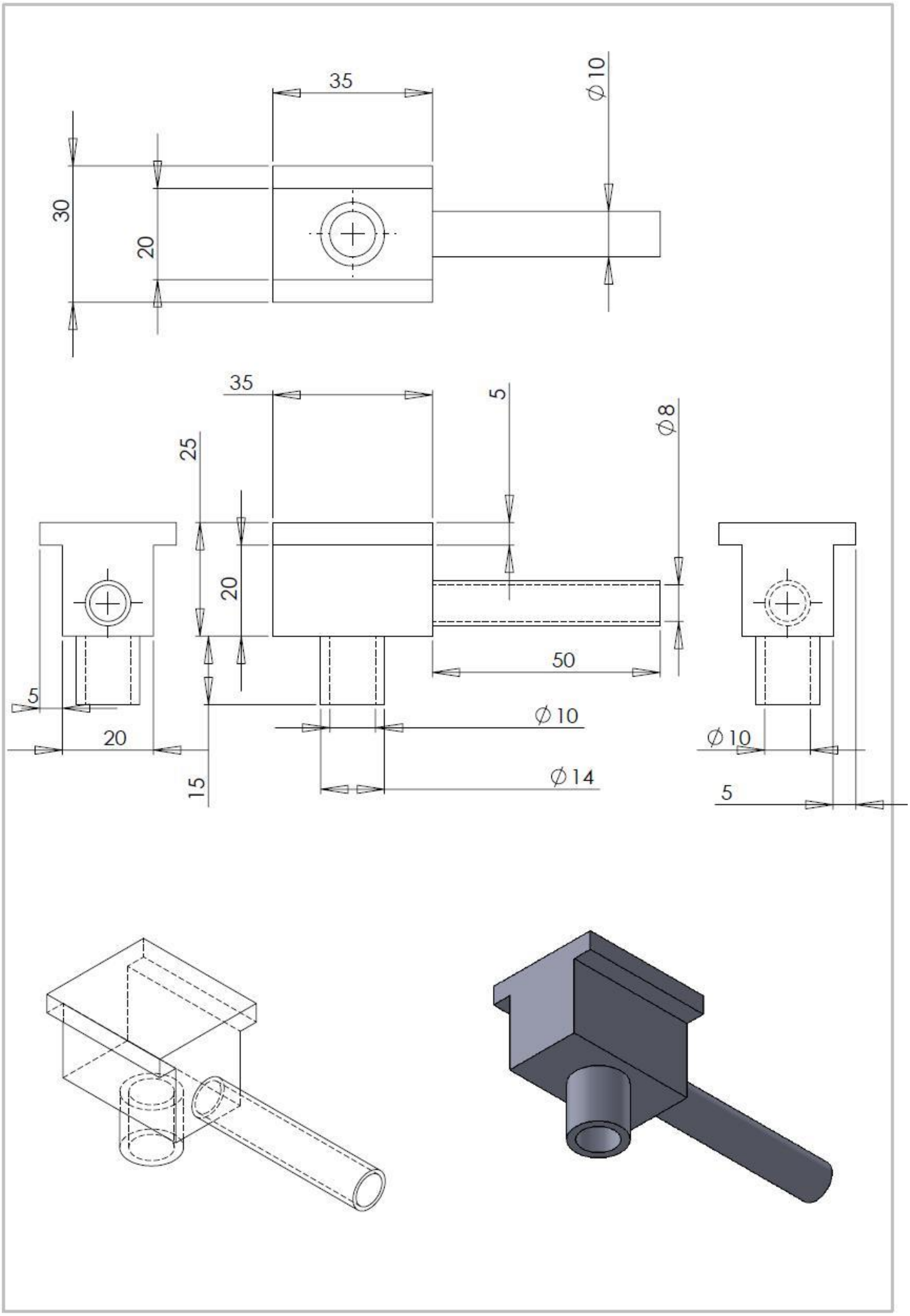
SUPPLEMENTARY MATERIALS

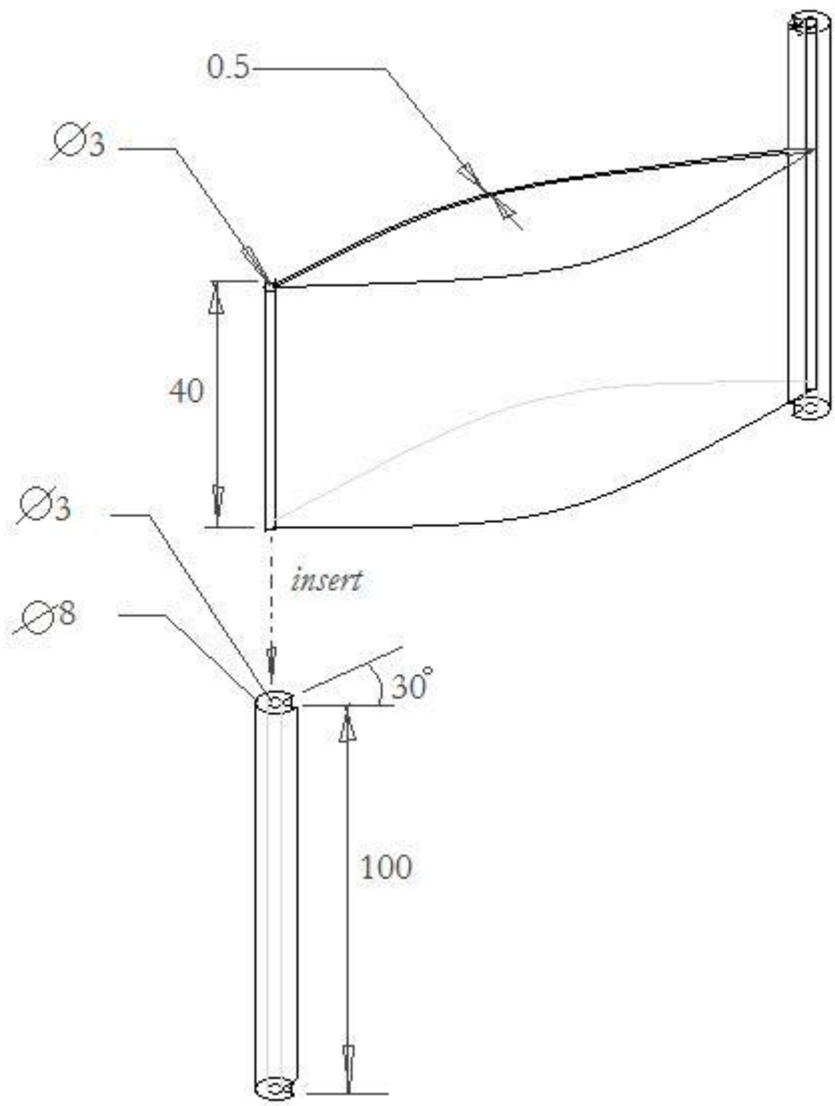
Below are detailed drawings for the fabrication of a commercial version of the robotic gripper:



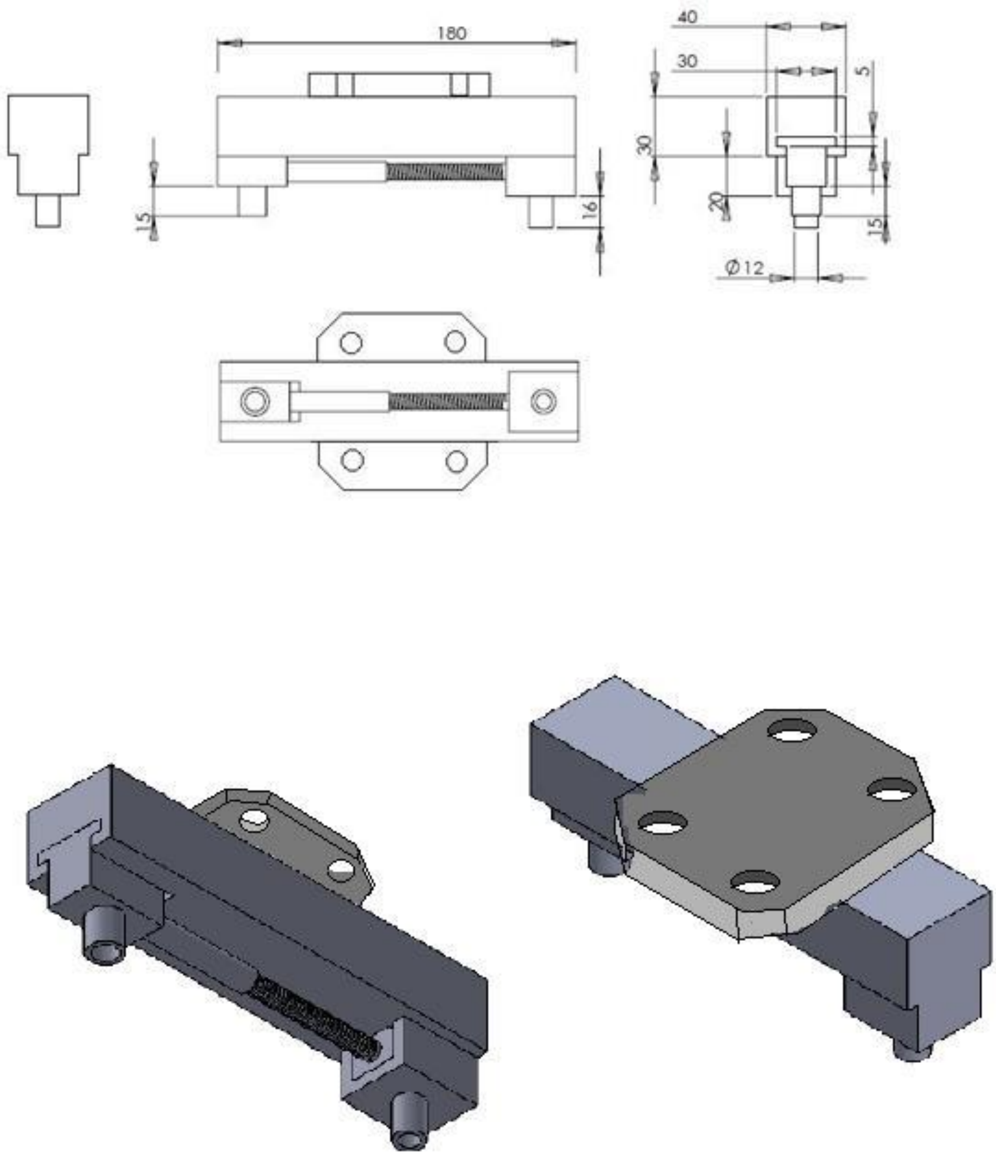
Actuator body



Slider



Gripper anchor and PET strips



Assembly drawing (actuator section)