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DESIGNING A FULLY COMPLIANT ROBOTIC ARM, END-EFFECTOR GRIPPER

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ABSTRACT

There is a lot of demand in the growing field of soft robotics for good alternatives to the classic robot arm end effector gripper. As most end effector grippers are generally mass-produced and because they are made from hard metals or plastics, they are unfit for soft robotics and are also generally quite expensive. This project aims to design a fully compliant gripper that is easily able to attach to the end of a robotic arm and serve as a fully functional end effector gripper. As the application is specifically for soft robotics, and due to the constraints of the physical application of the gripper, it is necessary that the gripper is a constant-force mechanism. This means that for a certain period of the input displacement, the output force would be constant for a while before increasing again. Constant force is required because, if we were to say the input force is derived from a generic servo motor arm, the force would have to linearly increase as we grip something. Instead, what we want is a constant force provided by the servo motor which ensures whatever we are grabbing is fully secured and does not fall off with constant pressure. The primary reason for converting a traditional rigid end-effector gripper with motors and rigid members into fully compliant is because of the multiple benefits that come with compliant mechanisms. This includes having a lower part count, reducing costs for assembly and manufacturing by cutting labor costs and ensuring it is one piece that can be cheaply 3D printed at a large scale. Furthermore, the application and scope for such a design can be for anything involving soft robotics including applications like autonomous manufacturing and packaging for delicate objects.

Keywords: Compliant Mechanisms, Compliant Gripper, Constant Force Mechanism.

1. INTRODUCTION

This paper will outline the design process, iterative prototyping and kinematic analysis conducted to completely design and print a fully compliant gripper from scratch. A regular compliant mechanism force diagram would generally

follow Hooke's law and therefore the force would be directly proportional to displacement, resulting in a perfectly positively sloped linear line. However, for this application we are striving for a constant force mechanism meaning the force diagram can no longer be perfectly linear and must include a region where the force remains constant for a period of time when input displacement keeps increasing. This can only be achieved with very specific design changes which are made to result in constant force mechanisms. These design changes are often to do with the geometry of the shape and the specific design choices and decisions to do with the order and orientation of the various modules of the mechanism such as sliders, springs and pin joints.

Figure 1 shown below is from a paper which specifically aimed at achieving near constant force for the largest possible input displacement amount [1]. Nevertheless, as the graph depicts, even with having that as the sole goal, it was only achieved for around 4 mm of input displacement. This shows exactly how difficult this is to achieve because of the extreme complexity in designing such a mechanism, analyzing its force-displacement relationship and then iterating multiple versions with minor changes to see which is most efficient and works the best.

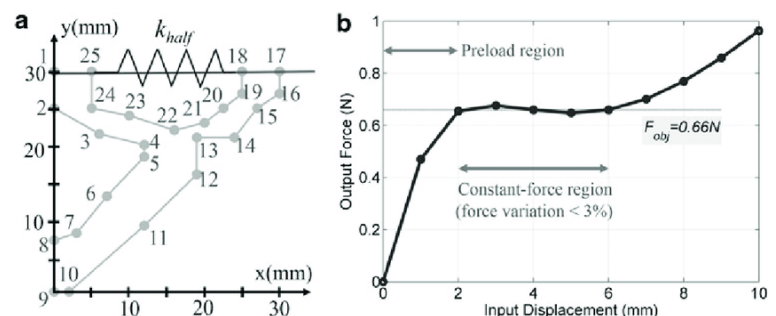


Figure 1. Constant force compliant mechanism example graph

Another key aspect of the design is that the opposite end to the prongs that act as grippers, must be a mechanism that allows easy installation to the end of a robotic arm. The two most straightforward ideas were to either have a screw thread to just screw in the gripper or to have a snap fastener type mechanism which would allow the gripper to just snap onto the end of the robotic arm.

2. MATERIALS AND METHODS

2.1 Design

The proposed compliant gripper design was inspired by a classic slider crank mechanism which is manipulated in a way to form a gripping motion. A basic slider crank design can be seen below in Figure 2, picked up from the internet [2]. The basic principle is that there are 3 links (including ground) with a slider, and as the first crank arm (r_2) rotates anticlockwise, it pulls the connecting rod with it which allows the slider to move horizontally as it is constrained to ground. Alternatively, instead of an input moment or torque, there could be a simple vertical force added to either the connecting link between the crank arm and connecting rod or to the top side of the connecting rod (r_3) itself. This configuration would assume the initial, stable position is already deflected with the crank arm and connecting rod at or near a 90-degree angle. The basic principle to this design is lining up 2 sliders co-linearly which would then give us the desired gripping motion.

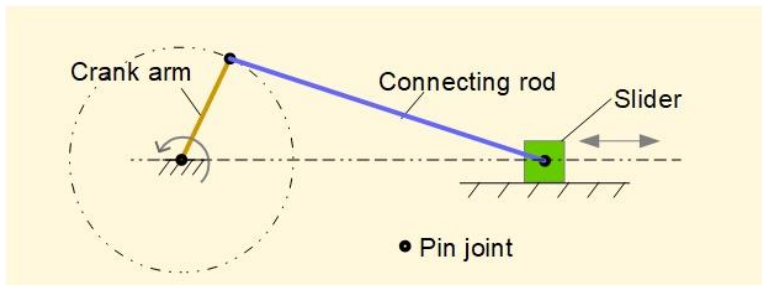


Figure 2. Classic slider-crank mechanism diagram

Now the crucial part of this design would be using this basic mechanism, but have it act with constant force, and preferably through a single input force load. To achieve this, the design would have to adhere to certain design principles, outlined by Dr. Howell in his book titled 'Compliant Mechanisms' [3]. Figure 3 illustrates all the potential configurations of a simple slider mechanisms which would allow for constant force. For this project, class 3A was chosen as it includes no pin joints and therefore can be manufactured as one piece and then no assembly is required either.

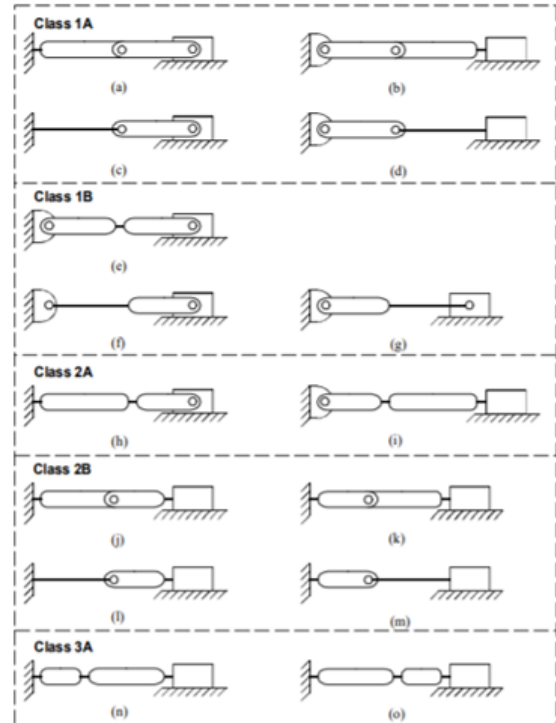


Figure 3. Configurations of constant force mechanisms

Furthermore, the precise lengths and dimensions also must adhere to these requirements in order to attain constant force. These dimension requirements can be seen outlined in Table 1 with constants in nondimensionalized form. These values will be defined later in the paper when the math is being discussed.

Table 1. Dimensional Synthesis for all Classes of Constant Force Mechanisms in Nondimensionalized Form.

Class	$\Delta x / (r_2 + r_3)$	R	K_1	K_2	Ξ	Φ
1A	0.16	0.8274	—	—	1.0030	0.4537
	0.40	0.8853	—	—	1.0241	0.4773
1B	0.16	1.0000	—	—	1.0564	2.0563
	0.40	1.0000	—	—	1.1576	2.1513
2A	0.16	0.3945	0.1906	—	1.0015	0.9575
	0.40	0.4323	0.2237	—	1.0058	1.0466
2B	0.16	0.7591	—	0.1208	1.0721	1.2259
	0.40	0.8441	—	0.1208	1.1914	1.2154
3A	0.16	2.6633	1.0000	12.6704	1.0002	3.4016
	0.40	2.0821	1.0000	9.3816	1.0049	3.6286

Using these basic principles, combining a simple crank slider mechanism in the form a constant force mechanism of class A, the initial design was formulated which can be seen below in Figure 4. The design inculcates a classic crank slider mechanism picked up from the compliant mechanism textbook [3] which should mean the mechanism is a constant force mechanism. As shown in the figure, the actual gripping is done by 2 rigid prongs which are connected to horizontal sliders that

can displace left and right. Pin joints are used to connect the sliders with some more flexible links which is connected to a vertical slider which can displace up and down. Once the bottom slider is pulled downward, this would force the compliant members together which would pull the horizontal sliders towards one another causing a gripping motion.

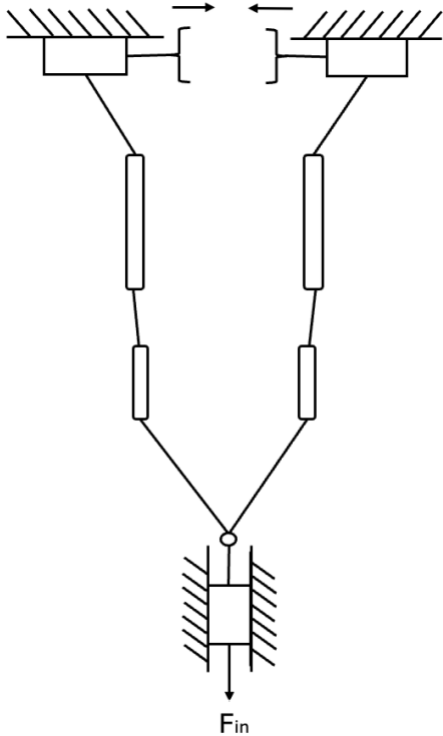


Figure 4. Initial proposed design for compliant gripper in a free body diagram model

This all sounds good in theory, but a practical test must be done before a CAD model can be made for 3D printing. This idea actually failed in the validation test when recreated on SolidWorks with lines and fixed joints. The intended motion was not achieved, and the two horizontal sliders never moved back and forth. Therefore, a swift pivot was required which led to an update in the design. Changes were made to retort back to completely horizontal mechanisms and a more classic slider-crank mechanism aesthetic. Figure 5 below shows the new and improved mechanism design. Aside from changing the orientation, the other major change was removing the pin joint connecting the input force piece and changing it into one single piece which connects to both connecting rods of the slider crank. Finally, Figures 6 shows the 3D printed final result after designing a CAD 3D model of the design on SolidWorks using the new and improved proposed design.

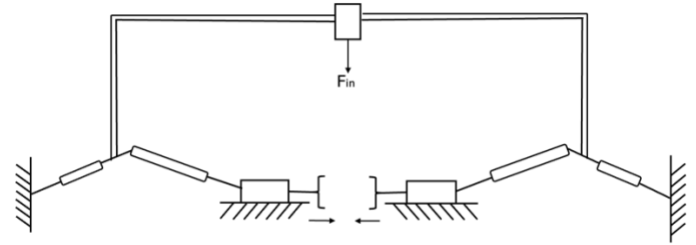


Figure 5. Second proposed design with changes implemented

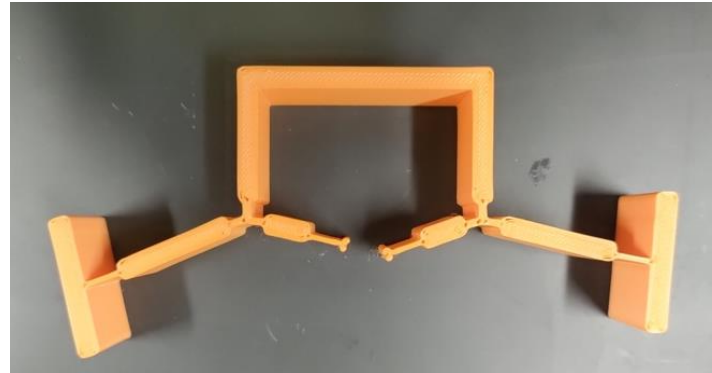


Figure 6. 3D Printed result of first prototype

After printing and tinkering with the piece for a while, it was clear that it did not perform up to expectations. There were a couple issues. First and foremost, the flexible flexures were modelled to be too thick, they had to be reduced down to something around the minimum nozzle line width of around 0.8mm. Secondly, the input force structure was rigidly attached to the flexible joint. The primary issue with this was when this piece is pushed down, the whole structure moves down as they are one piece. Even when the side pieces that are supposed to be ground are fixed, since the input force is at an angle, instead of moving the sliders horizontally, the sliders moved at that same angle. To address this problem, a constraint had to be added which allowed the sliders to only move horizontally and completely limit its vertical motion/movement. Additionally, since the rigid input force piece will also need to be grounded and this would limit its movement, 2D linear springs were added to the design to show the piece can move horizontally freely to allow the input force to work effectively. Serpentine flexible flexures were used to attain this motion modelled by linear springs. Finally, to properly ground the side pieces and overall provide further stability to the mechanism, an all-encompassing frame was added, and this could also be used to ground the rigid piece which would constraint the sliders movement.

Hence, after carefully noting the necessary changes and redesigning the model to reflect the changes, the third proposed design was created which can be seen below in Figure 7. This image includes arrows with descriptions of the primary changes made after learning from the last prototype. This design was

also CAD modelled on SolidWorks and 3D printed to form the 2nd prototype, which is shown in Figure 8.

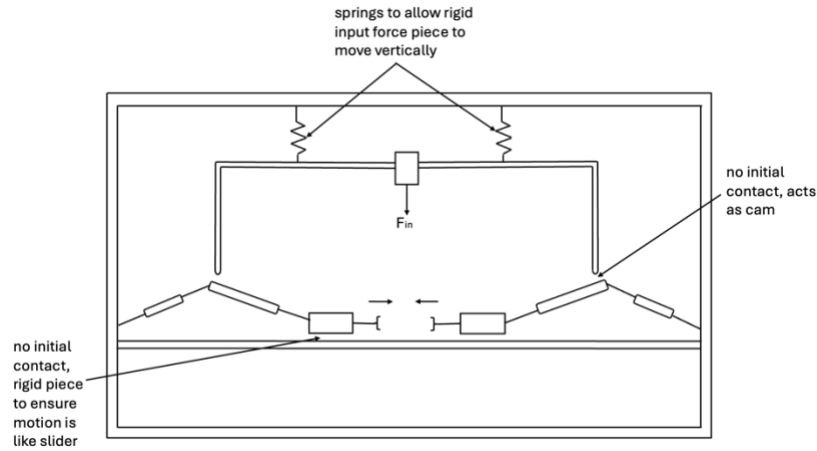


Figure 7. Third proposed design with further changes implemented

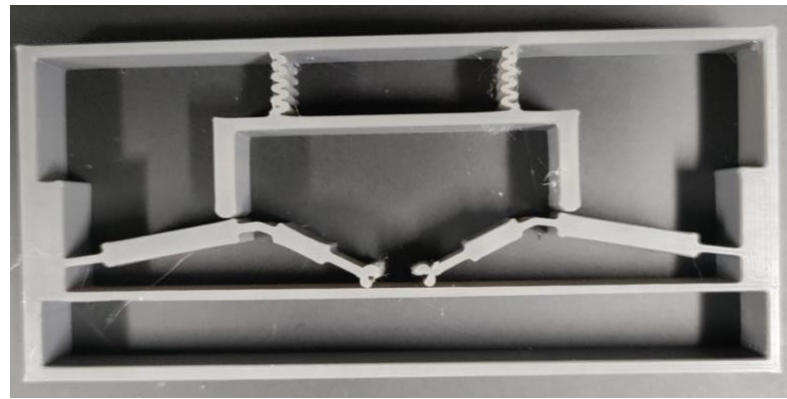


Figure 8. 3D Printed result of second prototype

This prototype also did not turn out ideal and had some key problems in its design. Namely, the rigid piece below the sliders which were added in to constrain the vertical movement of the sliders were modelled to be too thin and therefore were not able to effectively constrain the motion as they would deflect themselves. However, if that piece was held still manually and the input force was provided, the mechanism would work as desired, and a clean gripping motion was observed. Another key issue with this prototype was the overall size, it no longer matched the CAD dimensions as there may have been an error when exporting it to the slicing software. These final 2 changes were made, and a final prototype was printed which can be seen in the conclusion section as Figure 11.

2.2 Kinematic analysis

As mentioned in the previous section, the primary analysis and mathematics required to be carried out is regarding the dimensions which determine the spring stiffnesses and then using these values to establish a virtual work analysis on the pseudo rigid body diagram to correlate the input and output force.

As per Table 1, using the values of R and K_2 , we can calculate values of each dimension of the geometry. The expanded equations for what R and K_2 represent are presented below as equations (1) and (2). K_1 , as shown in the table, is equal to 1 meaning the spring stiffness for the first 2 springs should be exactly equal. Using these two equations, we are able to decide all our variable length value magnitudes so long as they adhere to these 2 equations. Equations 1 & 2 have been further expanded and the values for R and K_2 which are 2.6633 and 12.6704 respectively, have been plugged in and all the 'r' and 'k' values have been broken down to their equations using variables we already know/need to decide.

$$R = \frac{r_3}{r_2} \quad (1)$$

$$K_2 = \frac{k_3}{k_1} \quad (2)$$

$$12.6704 = \frac{k_3}{k_1}$$

$$k = \frac{EI}{l} \sim \frac{h^3}{l}$$

$$12.6704 \times \left(\frac{h^3}{l}\right)_{k1} = \left(\frac{h^3}{l}\right)_{k3} \quad (3)$$

$$2.6633 \times r_2 = r_3$$

$$2.6633 \times (L + l)_{r2} = (L + l)_{r3} \quad (4)$$

To briefly explain the steps that helped us arrive at equation (3), we were able to cancel out all the common factors between the 2 sides of the equals sign, which includes E , b , and $1/12$. The width, b , is left out as this makes the overall design a lot easier to make as the entire sketch can just be extruded an equal distance. Finally, utilizing equations (3) and (4), and choosing arbitrary values for other variables like the gripper displacement and output force, final variable length magnitudes were finalized. Instead of using an optimizing algorithm, the simple simultaneous equations were solved which helped determine the 'l' value and hence all other 'r' and 'theta' values were calculated. All these final values were input into SolidWorks and at the lowest energy state, theta values were measured from the sketch. All of these variable values can be found in Table 2 below.

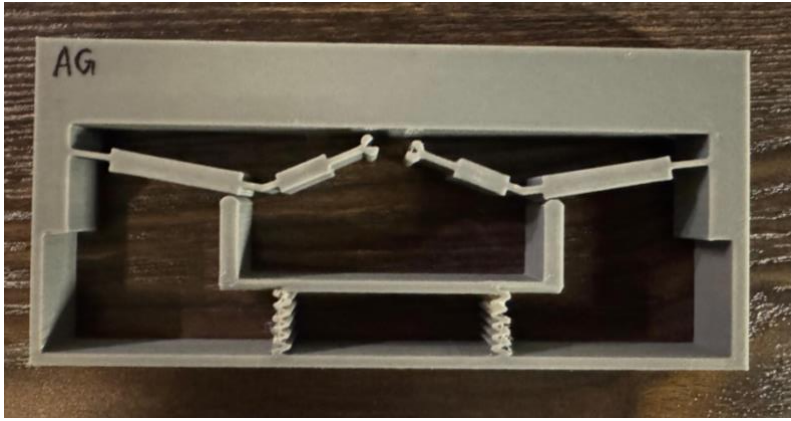


Figure 11. Final prototype, incorporating all changes from previous prototypes

The overall goal of having the mechanism be constant force was unfortunately not able to be conclusively tested. For a formal test, more time and resources would be required which were outside the scope of this project. As previously described, the design principles of constant force mechanisms were implemented and subjectively—to a human input force, the mechanism does feel constant force like. This does not mean that the input force is perfectly horizontal and constant throughout but instead feels like the graph shown in Figure 1. The input force is definitely a lot and increases linearly initially but tapers down and feels constant for a certain range of motion of input displacement and then increases again. This is of course extremely subjective, but this notion was supported by several other graduate students and seemed to be agreeable with Dr. Butler, someone with a Ph.D. and over a decade of top-notch experience in compliant mechanisms.

There are 2 other primary points of interest are conclusive/reflective thoughts on the design and kinematic analysis. First, if this design was physically implemented into an end-effector would it practically work and function as expected? More than likely, the answer is no. This is because the rigid piece which prevents the gripping sliders vertical movement and keeps it strictly horizontal would possibly interfere and conflict with the object that is being gripped or picked up. There is a clever work around this though- if the connecting arm (between the crank arm and slider) had an extra extruded piece perpendicular which was then constrained instead of the gripper itself, this design could potentially still work. However, this is something that can be considered future work and adds some scope for improvement. Another major potential improvement is to properly design the serpentine flexures that allow the input force piece to freely move vertically. As of now, since the serpentine flexures are designed extremely poorly, they do not bend and instead the thin beam they are attached to is bending instead. The desired motion is

analogous and remains identical, but this is a clear design flaw which needs to be improved upon.

Furthermore, as equation (7) points out, the mechanical advantage on this mechanism is awful. Mechanical advantage is defined as the ratio of the output force divided by the input force. For this mechanism, the input force was calculated as 166 N, and this input would result in an output force of only 100 N. In other words, the system essentially loses energy due to the springs and friction and other energy consumers in the system. However, this tradeoff is an important one as in return the mechanism achieves a very unique function with specific features—such as constant force. It is important to find a balance between a low mechanical advantage and the other features and qualities that are achieved with this design and mechanism.

4. CONCLUSION

This work presented the redesign of a traditional robotic arm end effector gripper into a fully compliant, constant-force gripper by leveraging the principles of compliant mechanisms, specifically, pseudo-rigid body models and the principle of virtual work to achieve a unique and effective design. The study highlights the integration of soft (flexible) and rigid members in a double crank-slider mechanism to form the gripping motion. Multiple iterations and prototyping validated the gripper's mechanics and its overall motion and its potential to be tested with a servo motor and real objects. The proposed design demonstrates significant improvements in efficiency, reducing part count and the overall cost of production of a robotic end-effector gripper—offering promising applications in manufacturing, automation and robotic manipulation. Future research can explore further design optimization and scalability and fine-tuning the design and dimensions for potential industrial deployment.

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