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DECLARATION

This report entitled

Stiffness controllable soft rotary robot actuators

Was composed by me and is based on my own work. Where the work of the others has been used, it is fully acknowledged in the text and in captions to table illustrations. This report has not been submitted for any other qualification.

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Abstract

The aim of this project was to design and manufacture a stiffness controllable soft rotary actuator that can be used instead of electrical motors. It also had to ensure safe human-robot interaction which would reduce the potential danger to people who come in contact with robotic systems. As a result, an actuator was designed that would be able to rotate by at least 90 degrees. This actuator would be attached to a shaft by the means of external rigid parts. The method used for manufacture involved covering the designed moulds with silicone material in order to create the soft actuator. The resultant actuator was suitable for applications that require maximum 90 degrees of rotation since the soft section only rotated by that much. It was made out of silicone which a soft and easily deformable material and is safe for human-robot interaction.

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1. Introduction

Industrial robots are the main driving force in the field of robotics nowadays. They are utilised in most of the industry and daily life. However, the safety issue is stagnant when the interaction between robots and people is the concern. It arises from the fact that the robots, which are driven by electrical and hydraulic motors, can injure the surroundings when malfunctioning. According to Occupational Health and Safety Administration in United States of America, robots were the results of 33 death and injury cases in the past 30 years in USA [1]. As such, there is a growing need for robots that can work efficiently in industry and be germane for safer robot-human interaction. Soft robots are the possible solution to such conundrum due to their biologically inspired characteristics.

1.1. Aims and Objectives

The aim of the project is to design and build a stiffness controllable soft rotary actuator that can replace modern electrical and hydraulic rotary actuators, while providing safe robot-human interaction. An actuator is a system that converts energy to work. This project addresses the safety by employing pneumatic actuation as the means to drive the soft actuators. As such, a user can safely interact with the system since it is constructed using soft and easily deformable materials. Furthermore, during a malfunction, the actuator can be degassed.

In order to create such an actuator several objectives are outlined. Firstly, it is essential to establish the performance of the actuator. In this particular case, the angle of rotation and the connection to the robotic links are the trivial components. The rotational angle range determines how much the robotic link would rotate, hence indicating t its performance. If the maximum angle of rotation is 90 degrees, the link is only applicable for applications that require no more than the specified angle, hence performance is defined.

Secondly, the design that would allow the actuator reach such a degree is another objective. It has to be simple enough to assemble, which allows for an ease of usage for various applications. For example if the actuator is malfunctioning, the simplicity of the design would allow to quickly determine the source of the problem.

Finally, the connection between the links and the actuator has to be considered. The solution that would allow the actuator to be connected to the link will allow reaching the desired aim.

1.2. Literature review recap

While contemplating about the design of the rotary actuator, several projects were researched to draw inspiration from them that could help with the design for the soft rotary actuator. These research projects have been extensively discussed in literature review. However, there were two designs that had impact when brainstorming upon the possible rotary actuator design.

First design that was analysed was a rotary actuator that was driven pneumatically by timed inflation and deflation of elastic bladders within the structure of the rotor. This design used four elastic bladders attached to four corners of the rotor and the pneumatic actuation of this rotor was based on the principle of peristaltic motion (sequential motion). Figure 1 shows the working principle of this actuator.

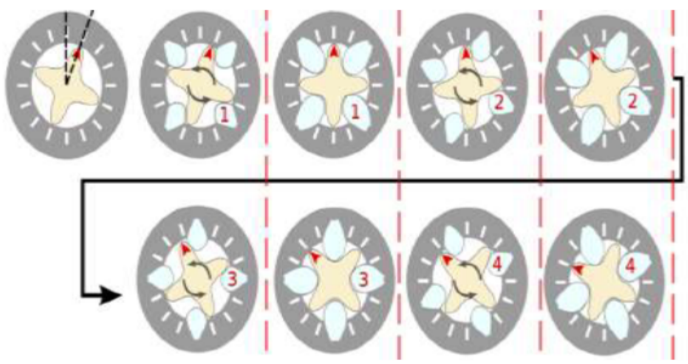

Figure 1. Rotary actuator based on pneumatically driven elastomeric structures [2]

The principle behind this actuator could be used for this project in case when the soft robot is inflated in order to push the rigid structures within the design.

In addition, an inspiration was drawn from the research on soft rotary actuators that represent a bellow structure. This type of an actuator used inflatable elastomeric balloons that inflate in a synchronized manner reaching an angle of 90 degrees, which represents a bellow type structure [3]. Figure 2 shows this type of an actuator.

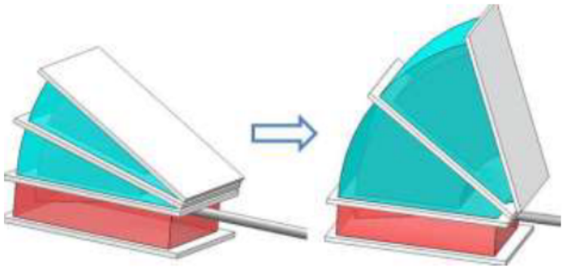

Figure 2. Bellow type actuator [3]

2. Design

2.1. Design criteria.

The main goal is for the actuator to be able to rotate a robotic link by at least 90 degrees. This can be achieved by employing the soft rotary actuators. The main working principle behind the design would be driving the soft elements, using pneumatic pumps which in return would activate the external parts of the actuator. A similar principle is used for the rotary actuators that are based on pneumatically driven elastomeric structures [2].

The design criterion for the actuator also has to address the connection between the actuator and the robotic link. In order to join the actuator with the links, the shaft connection was the choice. When the soft elements of the design are inflated, they would trigger the rotation of shaft. The reasoning behind choosing the shaft system is related to the stability and accuracy of rotation. If the soft section of the actuator rotates by 60 degrees, the shaft would rotate be approximately the same amount.

The position of the actuator in the overall robotic system is an additional concern. It defines the overall design specifications of the structure. For example, if a robotic arm is considered, and the goal would be to rotate the link that is fixed on the ground then the actuator would ideally have to be pinned to the ground to ensure its' stability. If the actuator is placed between two robotic links, then such solution would be inadequate. In this project, this design issue is attended to by focusing on the platform on which the soft actuator is positioned. This issue can be seen using figure 3.

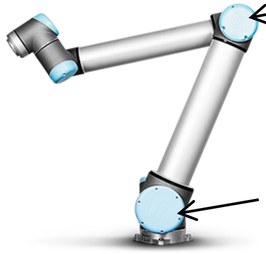

Figure 3. A robotic system with rotary actuators on the base and between two links [4]

In figure 3 a robotic arm system has two actuators; one fixed on the base and another fixed between two robotic links. As such, it is important to make sure to know at what position the design will be placed; between two links or fixed to the ground.

Finally, the soft sections of the actuator have to be expanding in the direction desired when air is introduced into the system. In order to achieve that the soft sections have to be reinforced in order to prevent expansion in unwanted directions.

2.2. Design implementation

There are several directions that can be taken in order to design a system that would achieve the goals, outlined in section 2.1. For example, if a bellow type design is considered, it would allow achieving the rotation of 90 degrees and above and it would be stable during inflation and deflation [3]. In addition, the connection between the robotic link and a bellow type actuator would be complicated. The idea behind should be a simple design that would integrate the soft actuator with the robotic system while performing its' tasks efficiently. As such following design was created using Solidworks.

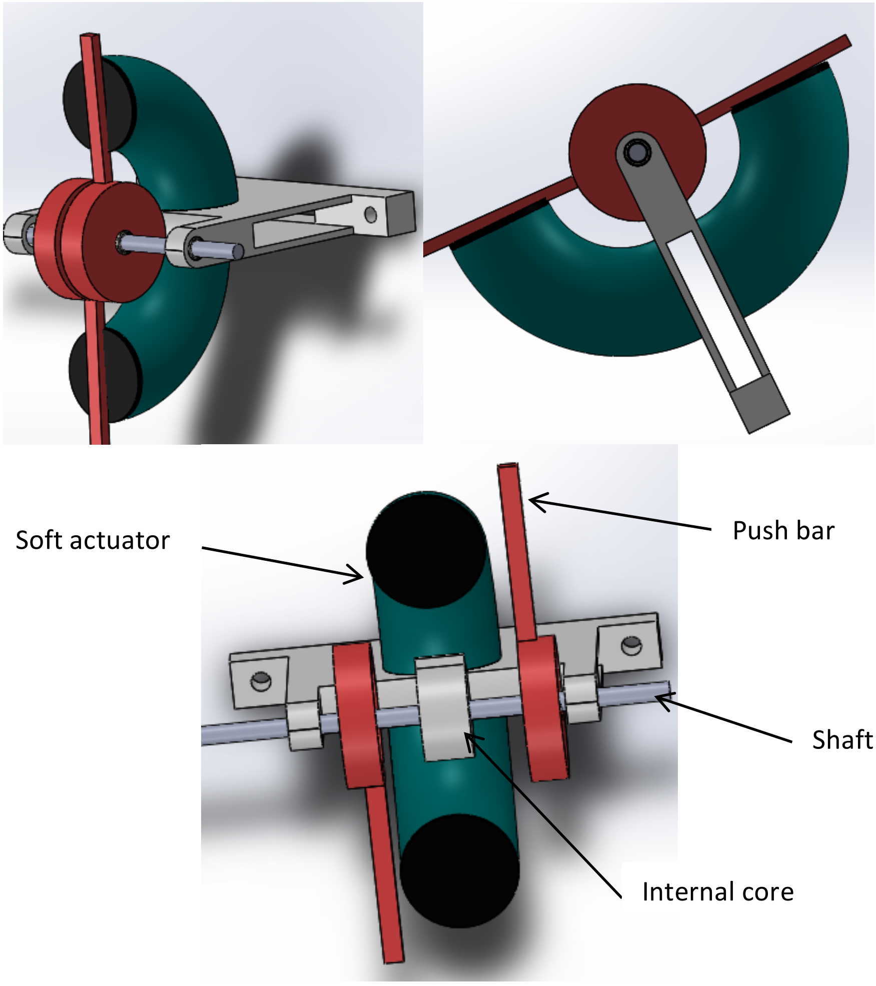

Figure 4. The design of the stiffness controllable soft rotary actuator using external parts.

Figure 4 above shows the design of the stiffness controllable soft rotary actuator that will be used to build the overall system. Each part in the figure was designed separately and assembled together since it simplified the manufacturing process.

The main idea of this system is for it to be able to rotate between 0 and 180 degrees. However since the soft element of the actuator becomes highly unstable during pneumatic inflation, it is hard to predict whether or not it will reach the required range of degrees. As such it is assumed that the actuator would have to reach at least 90 degrees in its rotation. However, this limits the range of applications such actuator can be used for. The main feature of this design is that in theory, it can rotate back from 180 degrees to 0 degrees. As a result two soft elements are used; one of the soft actuators rotates clockwise while the other rotates anticlockwise. This allows fixing the rotation at angles given in the established limit above. For example, if the actuator has to be rotated by 60 degrees clockwise, the first actuator can be inflated, while the other actuator would be deflated by the same amount.

After reaching the specified degree, if it is required to rotate the actuator to a position which would be equal to 40 degrees clockwise rotation, the actuator that rotates anticlockwise would inflate rotating by 20 degrees, while clockwise rotating actuator would deflate by 20 degrees. As such this would allow a stable control of actuator positioning. The control system that would allow such actuation behaviour would have to keep track of the air pressure coming from pneumatic tubes, which are attached to both soft actuators on the overall design, and adjusted accordingly.

2.2.1. Design of the soft actuators

It is evident from above that the soft rotary actuators are the essential part of the overall system since they are the main system driving force. As such the design of these actuators and the accuracy in their dimensions is integral.

To achieve a rotary motion, the soft actuator shape has to be suitable for that. As such going with a curved shape is an ideal choice. This is due to the fact that during pneumatic inflation, the growing air pressure inside the actuator would increase, acting on the front wall (cross section) of the actuator which would cause the actuator to expand forward. Since the shape of the actuator is curved, such design would cause the actuator to rotate during, actuation, rather than expand forward. This behaviour is closely related to PneuNet bending actuators with strain limiting materials that use a rigid material to restrict the increase in strain during inflation which causes bending [5]. However, there is a problem of undesired radial expansion that has to be dealt with.

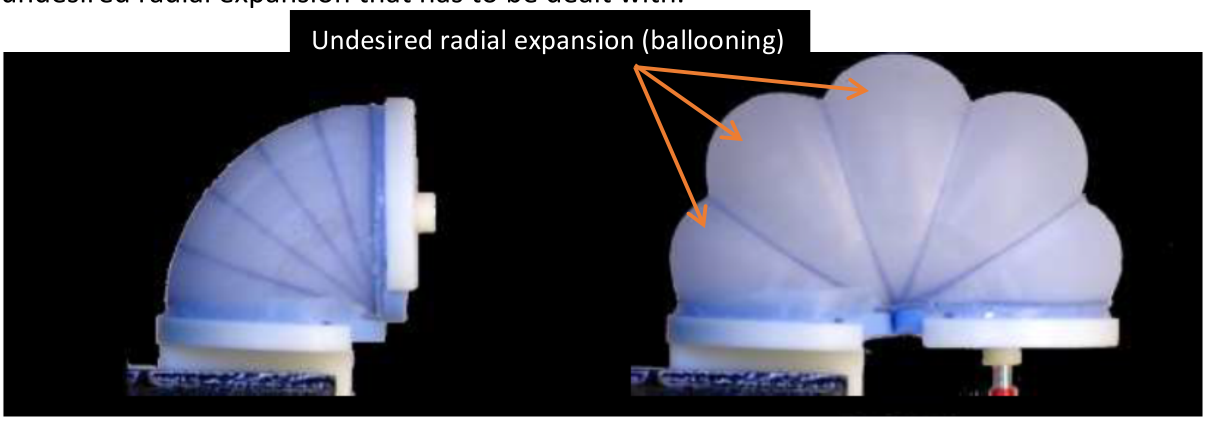

Figure 5.Soft rotary actuator with undesired radial expansion [6]

Figure 5 shows the soft rotary actuator that has ballooning occurring round it. This ballooning is an undesired expansion that has to be restricted. For the design of the soft actuator, it is intended to add filament winding around the actuator in order to reduce the number of ballooning occurring [6]. As such the actuator was wrapped with a nylon thread.

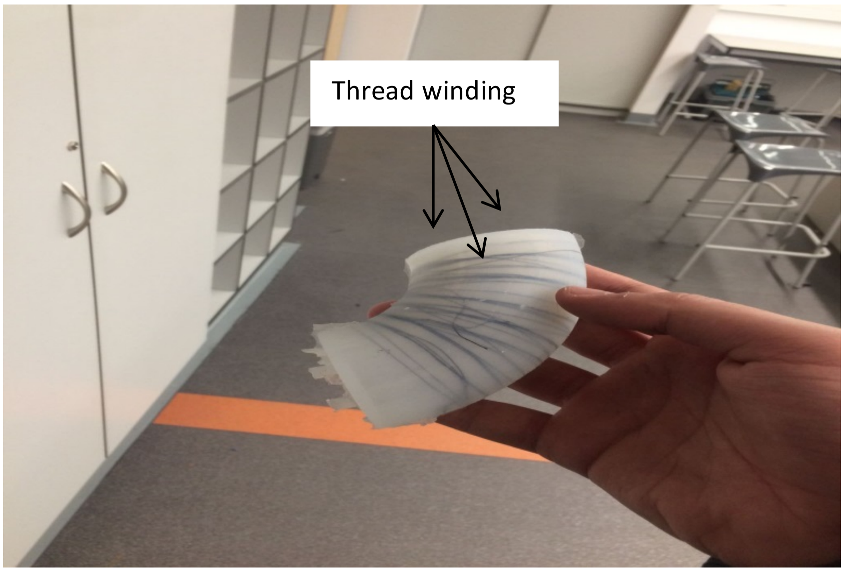

Figure 6. Thread winding around the actuator

Figure 6 shows the manufactured prototype soft actuator with a large amount of thread winding to prevent large ballooning. The manufacture process of the soft actuator will be addressed later in the report.

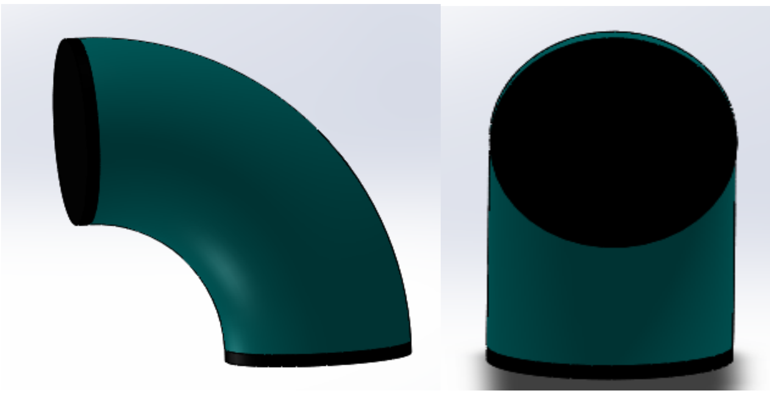

Figure 7. Design of the soft actuator

Figure 7 shows the design of the soft actuator. The cross sectional area of the actuator is 48 mm in diameter and the radius of the curvature is approximately 35 mm. Such curvature allows the actuator to rotate at the given radius, provided that the thread winding is present

2.2.2. Design of the base platform

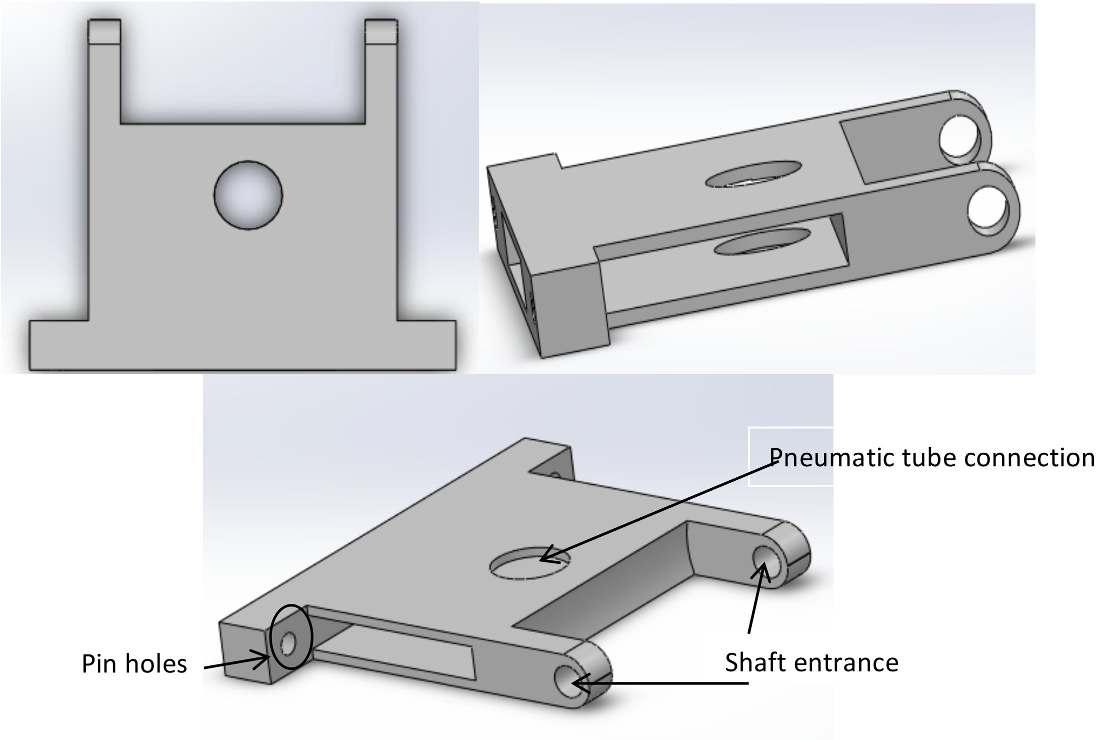

Figure 8. Design of the base platform

Figure 8 shows the design of the base platform where the soft actuators, the shaft, core and the bars are placed on. The extruded holes on the surface of the platform are the entrances for the pneumatic tubes. The soft actuators are placed on top of the entrances which are of 10 mm radius. This allows safely placing the actuator and freely connecting them with the pneumatic tubes.

The two symmetrical bars extending out of the platform allow maintaining a safe distance between the shaft and the platform which facilitates a rotation with no interference. This is also true between the outer bars and the platform. The shaft entrance holes also include ball bearings that are imbedded into them in order to make sure that when the given shaft rotates, it does not affect the stability of the platform. As such, rotating the shaft would not rotate the platform.

As mentioned in section 2.1 of the report, one of the criteria for the design is the stability and position of the actuator. This is directly related to the design of the base platform. As can be seen from the figure above the platform design has pin holes. This is done because the platform is going to be pinned down to the ground. As such the overall design of the actuator is considered to be a base actuator that is fixed to the ground. This can be seen in figure 3.

The extruded cuts on the sides of the platform allow introducing the pneumatic tubes into the system. The overall dimensions of the platform are 149 mm by 140 mm (height x width).

2.2.3. Design of the core and bars.

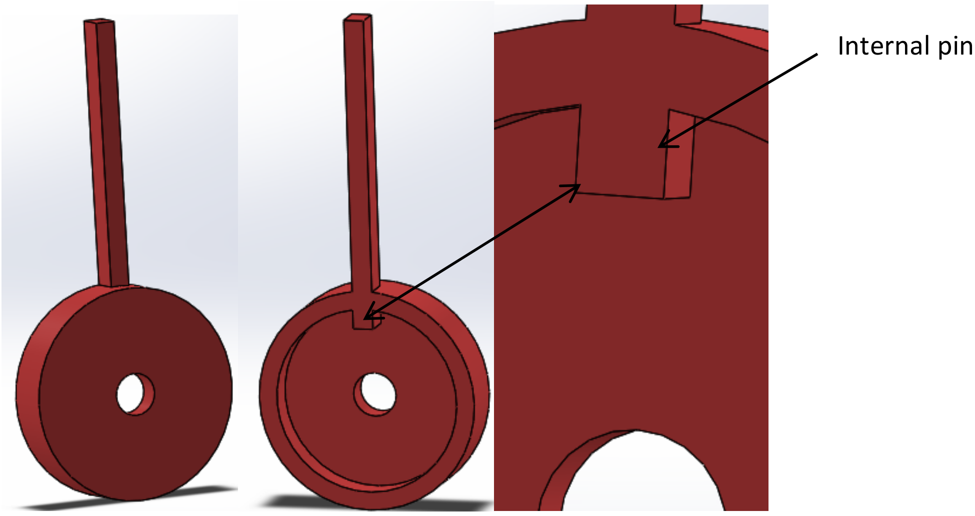

Figure 9. Push bar

Figure 9 shows the push bar that is attached to the shaft of the overall system. For that purpose the central hole is cut in order to place the ball bearings and the shaft through it.

The bars extending above the circular structure are designed so that the soft actuators, discussed in section 2.2.1, would be able to rest on them and during the inflation of the soft actuators, they would be pushed causing the rotary motion. The height of the bars was increased to approximately 76 mm. This is done due to the fact that at a certain point the inflating soft actuator might become unstable and might deviate upwards from the bar thus becoming misplaced. Since the pneumatic actuation is the hardest to control, after passing certain angles, such behaviour might occur. However, such height ensure that during instability the soft actuator would still be acting on the bars thus further rotating the overall structure.

The internal structure of this design includes a pin that facilitates the rotation of the core. In addition, the internal structure is part hollow because the core is placed inside it. There are two push bars and the core is placed between them.

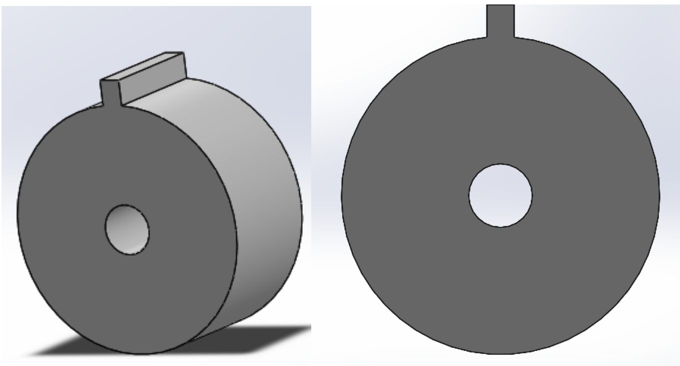

Figure 10. Internal core

Figure 10 shows the internal core of the overall rotary actuator. This core has a central hole that is used to pass a shaft through it. It has a pin on top of it that is in contact with the internal pin of the outer bar since the core is rotated by rotating the pin on top of it with the internal pin from the outer bar. The overall dimensions of the core are 44 mm by 40 mm by 20 mm (height x width x depth)

The overall dimensions of the outer bar are approximately 137 by 68 by 8 mm (height x width x depth).

2.2.4. Design operating principles

The operating principle behind the rotary actuator included several chains of actions. First, the control board provides pneumatic actuation to the soft actuators. The pumping to each of the soft actuators is controlled.

To elaborate on the working principle of the actuator an example of clockwise rotation is considered.

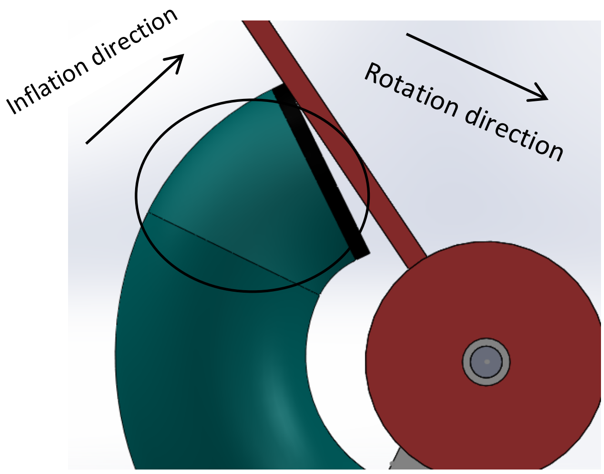

Figure 11. Inflating the actuator, the bar rotates as a result

Figure 11 shows the clockwise rotation of the actuator when the soft actuator is being inflated. As a result of air being introduced into the system, the soft actuator that rotates clockwise inflates, pushing on the push bars. Since the bars and the soft actuator are designed to rotate during inflation, the outer bar will rotate around the shaft.

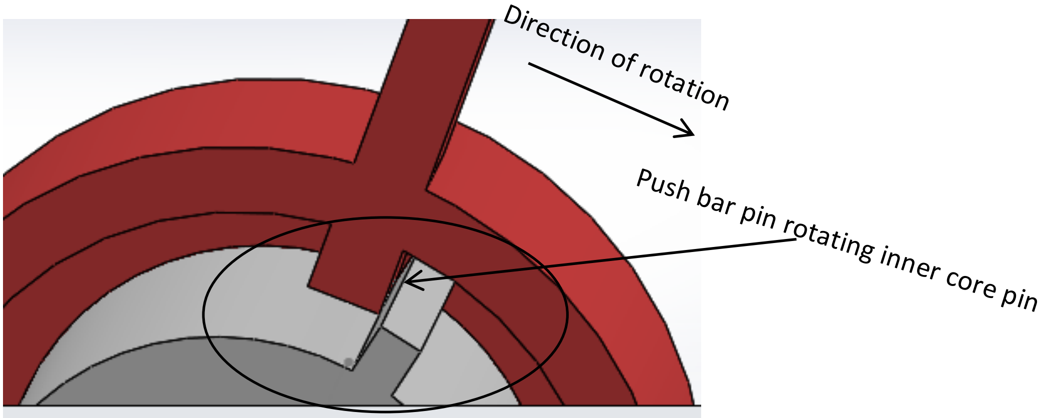

Figure 12. Rotating bar connects with the pin of the core

Secondly, during the rotation, the internal pin of the outer bar acts on the pin that is placed on top of the internal core, which, as a result, rotates. This is illustrated by the above figure; the pin of the outer bar is in contact with the pin of the internal core.

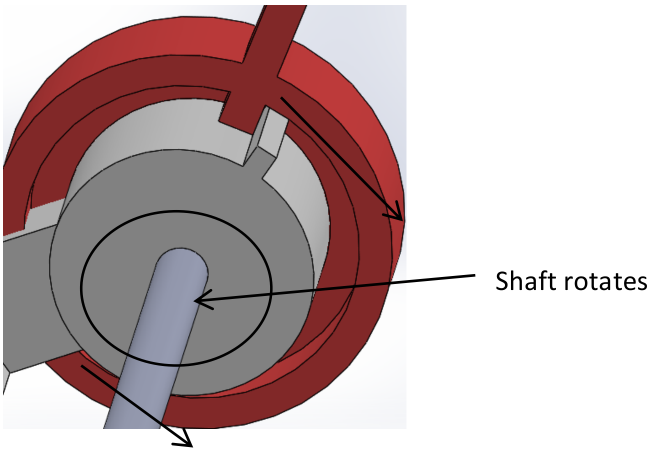

Figure 13. Internal core connected with the shaft causing it to rotate

Figure 13 shows the connection between the internal core and the shaft. These two structures are bonded together. Therefore the rotation of the internal core would cause similar rotation of the shaft. As a result, this mostly ensures a precise control over the rotation of the actuator.

The overall system, as mentioned before, works as a chain reaction. The pneumatic actuation causes the rotation of the soft actuator, which in return causes the rotation of the outer bar. The rotating bar causes the rotation of the internal core, which as a result, rotates the shaft. Due to this fact, if the soft actuator is rotated by 60 degrees, the shaft will approximately rotate by the same amount.

The second soft actuator at the bottom of the platform can be used to rotate the haft anticlockwise. As such if both soft actuators are employed, it is possible to control the rotation of the actuator and the shaft. For example of both actuators are inflated by amount that equals to 90 degree rotation, this will place both soft actuators at the same level. At this point it is possible to deflate one of the actuators, while inflating the other actuator by the same amount in order to cause either clockwise or anticlockwise rotation.

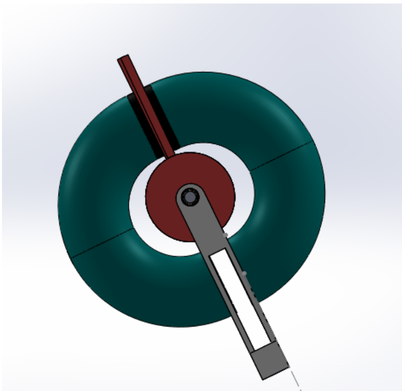

Figure 14. Both soft actuators inflated to 90 degrees

Figure 14 shows the actuator when the soft elements are both inflated by 90 degrees. As mentioned above from this point on, it is possible to control the rotation of any connected link between 0 and 180 degrees (however due to the nature of the soft actuators, it might become unstable after 90 degree rotation). For example if it is required to rotate the actuator from 90 degrees clockwise position to 60 degrees, the clockwise soft actuator will deflate by 30 degrees while the anticlockwise soft actuator will inflate by amount equal to 30 degrees rotation.

In addition to overall mechanics of the device, an issue concerning the stability of each part of the system during rotation arises; for example, when making sure that one of the outer bars does not rotate when the other is rotated. To do that, ball bearings are used.

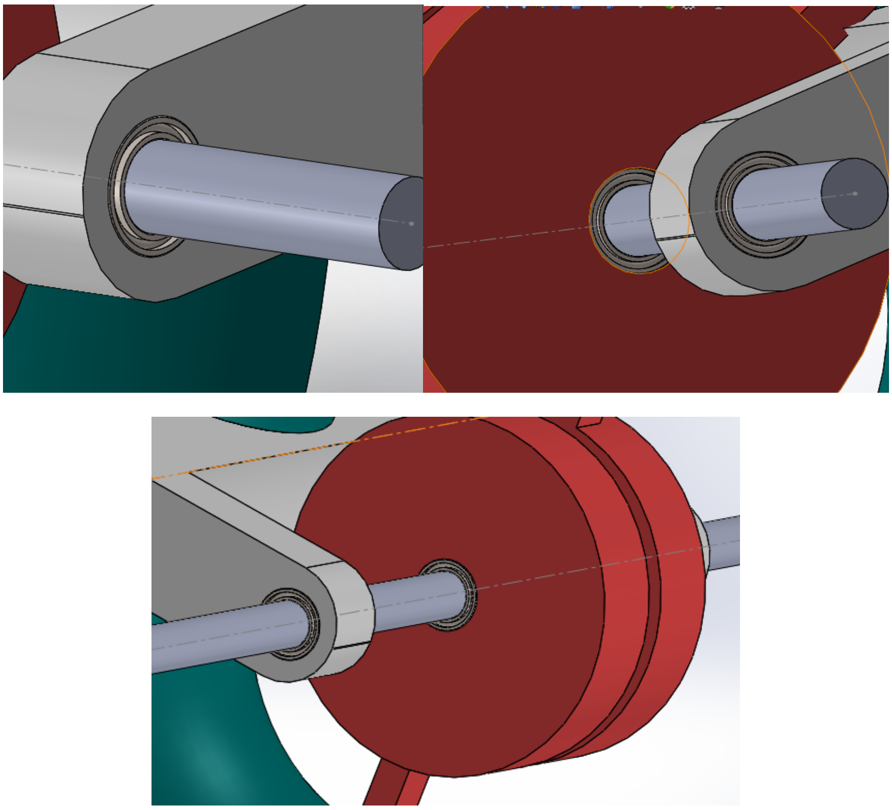

Figure 15. The ball bearings attached to the base platform and the outer bars

Figure 15 shows the overall system and how the ball bearings are used to keep the structure stable. If one of the bars is rotated, that does not necessarily mean that the second bar will rotate as well since the ball bearings are attached to both of the structures. The only structure that does not have ball bearings attached to it is the internal core since its purpose is to rotate the shaft by being permanently bonded to it.

3. Manufacture

The manufacture of the project primarily involves three stages: fabrication of the soft actuators and the fabrication of the rigid parts.

3.1. Soft actuator manufacture

3.1.1. Design of the moulds criteria

The manufacture of the soft elements of the design involves creating moulds in order to give the soft actuators the required shape as seen in section 2.1. There were several criteria that needed to be followed in order to make sure that the manufacture stage was successful. One of the criteria was the design of the negative mould (mould that has hollow sections inside).

The main issue addressed was the fact that the mould could possibly damage the silicone. As such, the design of the mould had to be created in a way that would not damage the soft actuator during the removal from the mould.

Another issue was focused on how to make sure that the soft actuator, during the manufacture stage, obtained the shape as seen in Figure 7. In order to do that, the moulds had to be designed to allow soft silicone to obtain such shape.

Lastly, the method of silicone injection in to the mould had to be considered. The mould had to have sufficient entrance for silicone in order to fill it.

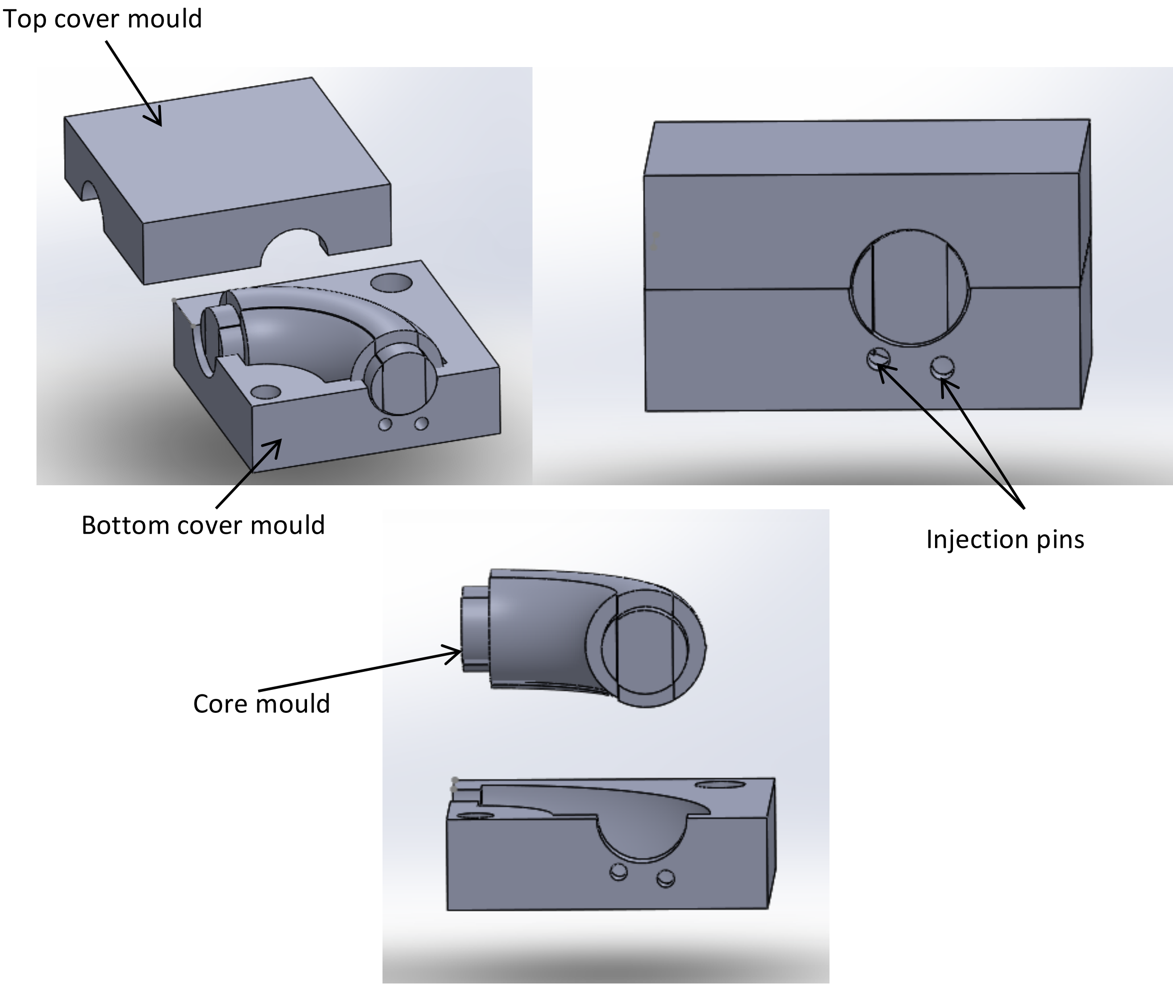

Figure 16. Core mould encased in cover moulds

Figure 16 shows the moulds that were designed for this project; core mould and the cover. It shows that the core mould is placed inside the cover and the silicone is injected through the injector pins.

3.1.2. Manufacture using moulds

The core mould is used in order to give the soft actuator its' shape. As a result, the form actuator obtains will facilitate its' rotation. Since the core is curved, the resulted actuator will have a similar shape and will inflate in a rotary direction. In addition, the shape of the core, allows the soft actuator to have a hollow internal chamber that is filled with air during pneumatic actuation. Thus, the actuator inflates.

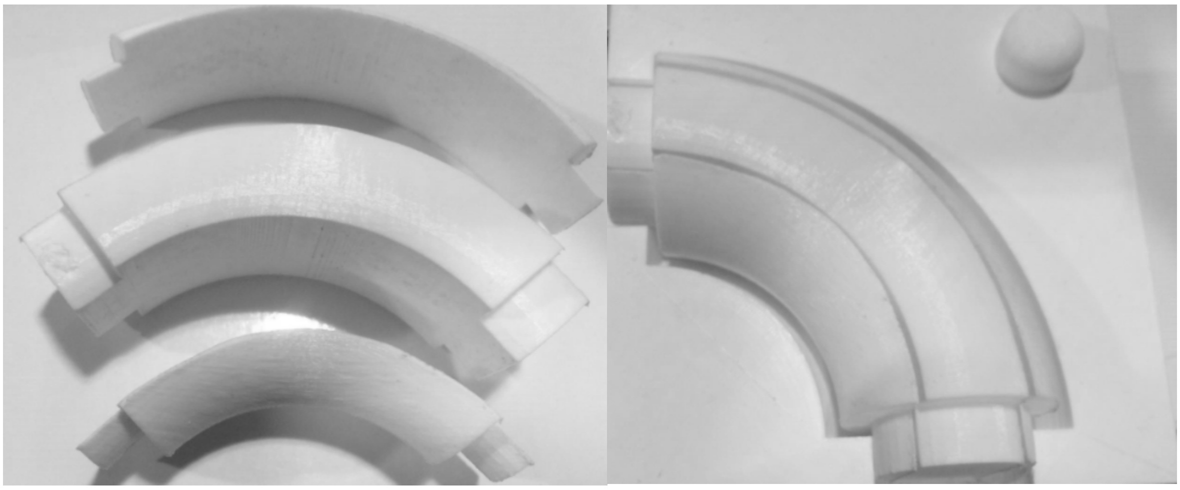

Figure 17. 3 part core mould

Figure 17 shows the core mould divided into three sections. This is done for reasons that are explained later in the report. During the injection process the silicone covers the mould and when left to cure, gives the silicone the shape of the actuator. The silicone used in this process is Ecoflex .

Ecoflex is a platinum-catalysed silicone that is versatile and easy to use [7]. It was important to choose the material that would have a low stiffness and be susceptible to deformations.

In addition to above mentioned, since silicone is a viscous substance, Ecoflex with the lowest relative viscosity was chosen for the core mould.

The tensile strength was also an issue. The soft actuator had to be strong enough not to tear during inflation, thus the silicone with the highest relative tensile strength had to be the solution.

The elongation which is one of the main criteria for the choice of material had to be sufficient enough for the actuator to inflate. By comparing different types of Ecoflex, the ideal silicone was chosen to be Ecoflex 0050.

TECHNICAL OVERVIEW

	Mixed Viscosity (ASTM D-2393)	Specific Gravity (g/cc) (ASTM D-1475)	Specific Volume (cu. in./lb.) (ASTM D-1475)	Pot Life (ASTM D-2471)	Cure Time	Shore Hardness (ASTM D-2240)	Tensile Strength (ASTM D-412)	100% Modulus (ASTM D-412)	Elongation at Break % (ASTM D-412)	Die B Tear Strength (ASTM D-624)	Shrinkage (in./in.) (ASTM D-2566)
Ecoflex® 5	13,000 cps	1.07	25.8	1 min.	5 min.	5A	350 psi	15 psi	1000%	75 pli	< .001 in./in.
Ecoflex® 00-50	8,000 cps	1.07	25.9	18 min.	3 hours	00-50	315 psi	12 psi	980%	50 pli	< .001 in./in.
Ecoflex® 00-30	3,000 cps	1.07	26.0	45 min.	4 hours	00-30	200 psi	10 psi	900%	38 pli	< .001 in./in.
Ecoflex® 00-20	3,000 cps	1.07	26.0	30 min.	4 hours	00-20	160 psi	8 psi	845%	30 pli	< .001 in./in.
Ecoflex® 00-10	14,000 cps	1.04	26.6	30 min.	4 hours	00-10	120 psi	8 psi	800%	22 pli	< .001 in./in.

*All values measured after 7 days at 73°F/23°C

Figure 18 Properties of different types of Ecofex [8]

Figure 18 indicates that an ideal choice for the soft actuator would be Ecoflex 5. However, it has 1 minute pot life which is not convenient for manufacture since it is essential to degas the mixture of Ecoflex A and B by at least 10 minute (ideal degassing time was found during trials) before applying on to the mould; Ecoflex A and B are the 2 parts of the silicone that need to be mixed together in 1 to 1 ratio before applying the silicone on the mould. As a result, Ecoflex 0050 was chosen since it had the 2^{nd} best mechanical properties and 2^{nd} lowest viscosity. In terms of pot life 18 minutes were more than enough in order to inject the silicone through the moulds.

The general fabrication of the soft actuator involved the following steps:

Step 1:

Ecoflex 0050 part A and B were mixed together and injected through the pins of the cover mould as shown in figures 19 and 20. The cover mould from figure 16 has the 3 part core mould inside it which means when cured the shape of the soft actuator would be created.

It was important to degas the mixture in order to reduce the number of air bubbles present in the mixture. For that purpose a vacuum chamber was used which is shown in figure 19 below.

Figure 19. Vacuum chamber

Figure 19 shows the vacuum chamber that has a magnetic mixer inside. As such, during mixing of Ecoflex 0050 A and B, the substance would degas at the same time that it is being mixed which brings more air bubbles to the surface. The rate of rotation of the magnetic mixer was increased to its maximum potential for the first 5 minutes in order to bring the most air bubbles. This allowed removing most of the visible air bubbles. In addition, to make sure that all air bubbles were gone, Ecoflex part A and part B were first degassed separately. To remove the silicone mixture from the chamber, the closed valve that blocked air from entering the chamber had to be slowly opened to let air in.

Figure 20. Injecting the silicone through the injection pins

Figure 20 shows the injection process for the soft actuator. It can be seen that the degassed silicone is injected using the syringe through the injection pins on the mould. However, even if this method is effective, there is a high chance of introducing air bubbles through the piston. Therefore, it was essential to inject the silicone slowly without forcing the piston in. After the mixture has been injected into the mould, it needed to be left to cure for approximately three hours.

Step 2

After the cure time has passed, the 3 part core mould with the silicone layered around it was removed from the base mould.

The three part core in figure 17 was designed as such for specific reason. It would be simple to design a core with a 90 degree rotation and apply silicon around. That would create a required soft actuator. However, the complication arises from the fact that it is very hard to remove the silicone from the mould without damaging it. As a result, three part core was created.

Figure 21. The soft actuator

Figure 21 shows the silicone covering the 3 part core. In order to remove the core safely without damaging the actuator, the centre core is removed first, followed by the top part and bottom parts of the core as shown in figure 22.

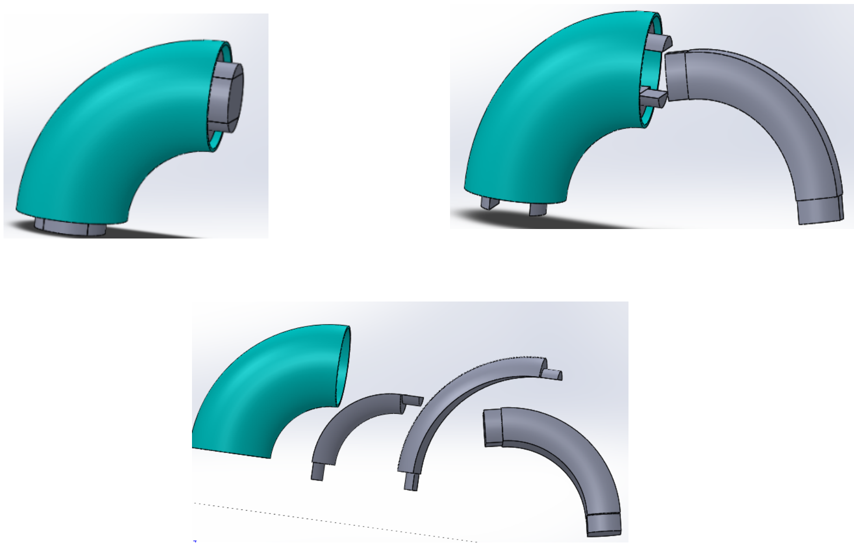

Figure 22. Core removal from the silicone layer

The threads wrapped around the core in figure 21 are used in order to keep the three part core together and when silicone is cured, the threads would be imbedded into the structure of the actuator. They are used to restrict the radial expansion of the soft actuator during the inflation; hence it prevents substantive ballooning happening during the rotation of the actuator.

Step 3

After the soft actuator has been removed, it was essential to close the front and back open cross sections.

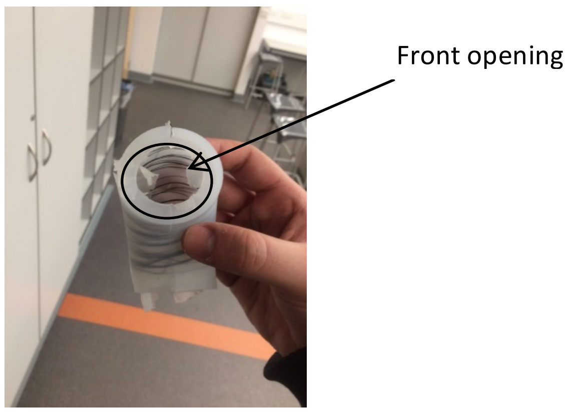

Figure 23. Soft actuator with front and back open and hollow

Figure 23 above shows the front open cross section of the actuator. In order to seal the gap, it was important to search for a material that would not be affected by air pressure acting on it. And it had to be able to bond with Ecoflex 0050. Smoothsill 950 was chosen as the possible material [9].

Smoothsil 950 is a stiff rubber silicone and can be used to bond with the front and back openings of the actuator in figure 23, thus sealing the gap. The soft actuator from figure 23 is dipped in to the mould filled with the mixture of Smoothsill 950 part A and part B. Smoothsill was not degassed because the material is stiff and the sample used to seal the gap was very small which means if there were air bubbles they would not be able to penetrate the layers of stiff rubber; therefore no requirement for degassing.

Figure 24. Soft actuator dipped into the mould of smoothsill 950

Figure 24 shows the soft actuator dipped into the mould of smootsill mixture. As such, the cross sectional openings are sealed. The cure time for Smootsill 950 is 24 hours which means to completely seal the actuator this time had to pass.

As a result the final form of the actuator with both ends sealed is shown in figure 25.

Figure 25.The final form of the soft actuator.

3.1.3. Trials and improvements

There were several trials that have been done in order to create the actuator. As a result of those trials, the errors that were found during the procedure were reflected upon and solutions were found. It is important to mention that in total there were 5 trials made, however the major problems worth mentioning are in trial 1 and trial 2.

Trial 1

During trial 1, 10 ml of Ecoflex 0050 part A and 10 ml of B were degassed separately (each 30 minutes) to minimize the number of air bubbles during mixing. Next, they were mixed (which made the total amount 20 ml) and degassed for another 10 minutes since the pot life during mixing is 18 minutes. The vacuum chamber used is the one from figure 18 . As a result, the mixture was free of major air bubbles that could damage the actuator. However, trial 1 showed that 20 ml of ecoflex mixture only covered half of the mould as can be seen in figure 26. As a result, 40 ml of ecoflex had to be used (20 ml of A and 20 ml of B).

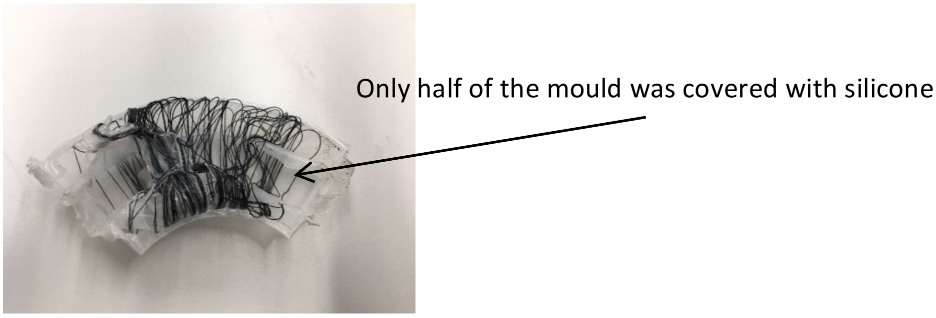

Figure 26. Trial 1 result.

Trial 2.

The same procedure as in trial 1 was performed with 40 ml of ecoflex. However, injection through the injector pins showed that it does not cover the top part of the mould fully which called for a different solution. As a result, 4 injection holes were drilled on top of the mould cover as can be seen in figure 27.

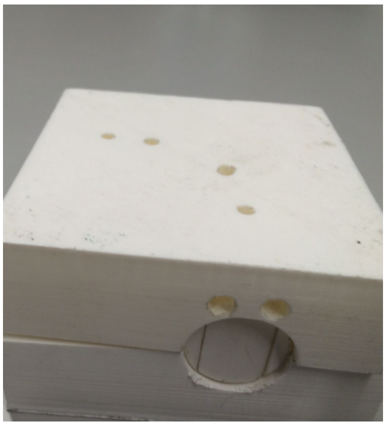

Figure 27. 4 injection holes drilled on top of the cover mould.

The new solution would allow covering the core mould completely. To achieve that, the bottom cover mould was covered first and let to cure. After that the 20 ml of degassed silicone was injected through the holes drilled in figure 27. As a result the whole mould was successfully covered in silicone. This can be seen from figure 28. At the end of this process the actuator was removed from the mould using the process described in step 2 of manufacturing process and shown by figure 22.

Figure 28. The final actuator product.

Figure 28 shows the final soft actuator that was made using the procedures from trial 2. However upon inspection, it had air bubbles that could be troublesome during inflation. This is shown in the figure 29.

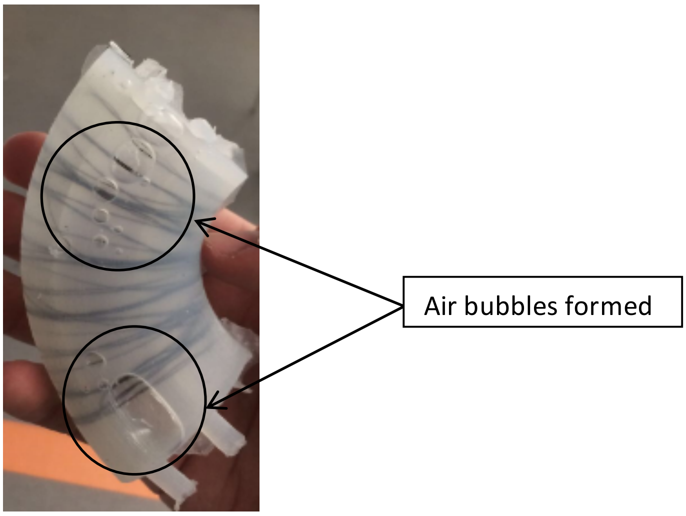

Figure 29. Actuator with air bubbles formed.

The most probable reason for these air bubbles was that during injection through the 4 drilled holes, the piston forced more air into the degassed silicone inside syringe, creating air bubbles. The improvement was made by covering the bubbles with another layer of degassed silicone. As a result, it was possible to inflate the actuator without air bubbles affecting the overall structure.

3.1.4. Testing the actuator

After a prototype of an actuator was successfully created, the testing was done by connecting the actuator with a pneumatic pump to measure the maximum angle of rotation. The main objectives of the test were to find out if the actuator can rotate, what problems arise during rotation and, if it rotates, how much can it rotate (in degrees).

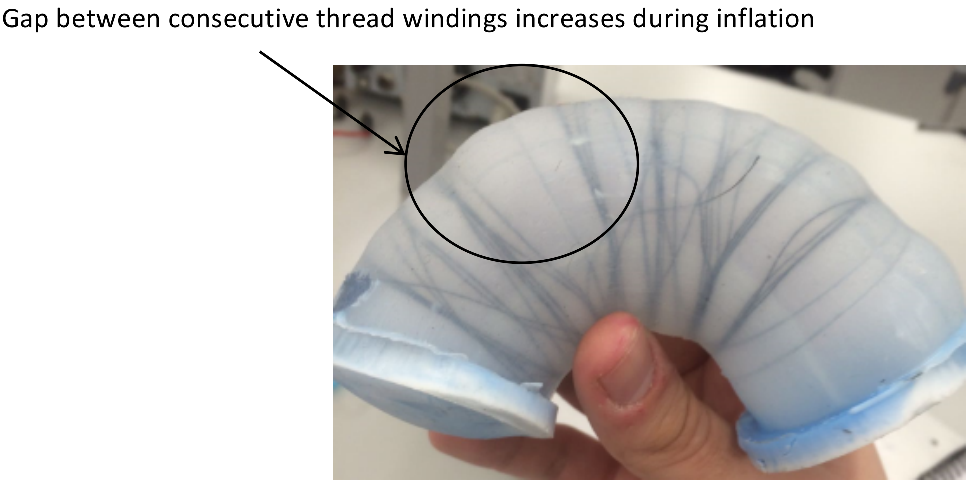

Figure 30. The inflated actuator

Figure 30 shows the actuator in inflated state. The problems that were arising during inflation were that as the rotation increased, the gap between thread windings was increasing creating ballooning which slowed down the rotation. In addition, it affected the linearity of rotation. As a result, to fix the problem, the actuator was winded with threads from outside.

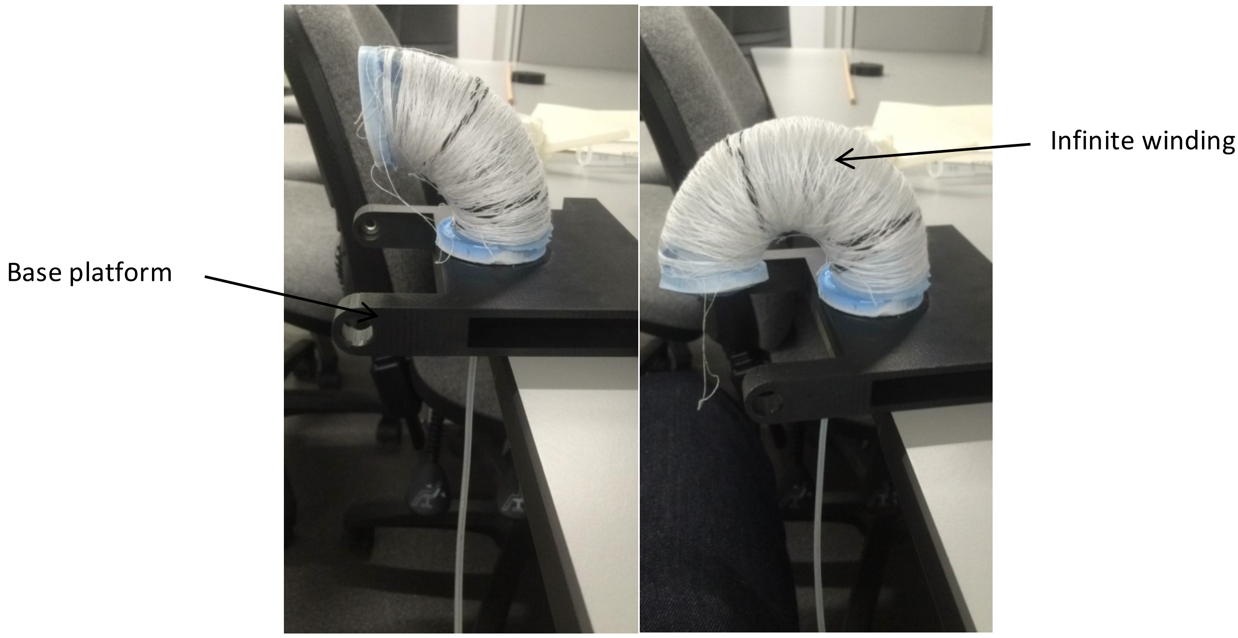

Figure 31. Actuator with thread windings outside (right deflated, left inflated). Anticlockwise inflation

Figure 31 above shows the soft actuator with thread windings outside rotated linearly relative to its initial position. Therefore, it was stable during rotation. The linearity of the rotation comes from the fact that the "infinite" winding was made to restrict the ballooning from every possible direction and so that during inflation the gap between each winding is small enough to not cause substantial radial expansions. The actuator rests on the base platform from figure 8.

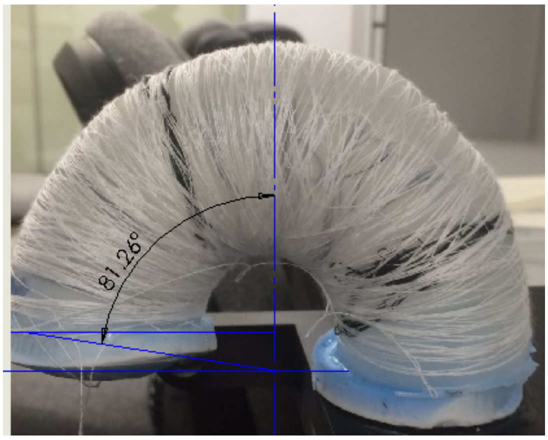

Figure 32. The maximum angle of rotation

Figure 32 shows the actuator inflated to its maximum potential. As can be seen, it inflates to approximately 81.3 degrees from its initial position. The goal is to reach the rotation of at least 90 degrees which is close to the value. The winding around the actuator is not even which affects the bending moment. This can potentially affect the rotation angle. In addition, DC pump used for the actuation is 6v dc air pump. Increasing the voltage of the pump can increase the speed of rotation and the angle.

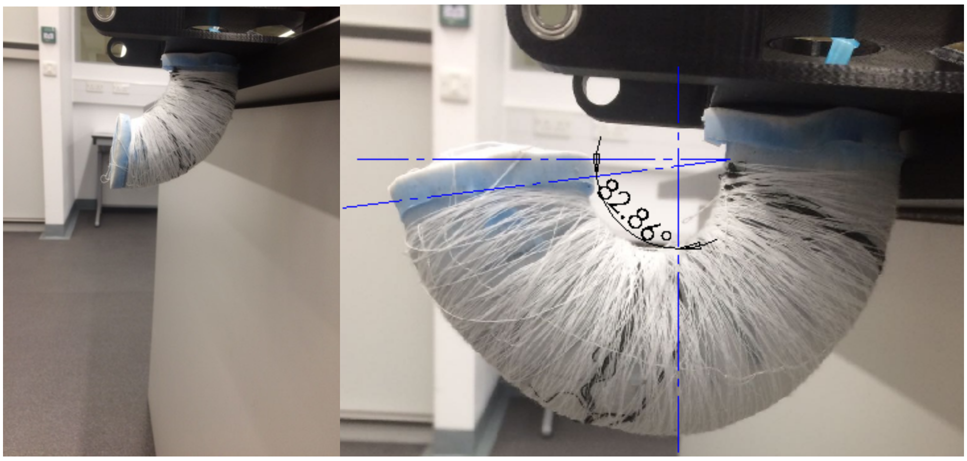

Figure 33. Actuator inflated clockwise

Figure 33 represents the soft actuator inflated from the bottom of the base platform in clockwise direction. It can be seen from the figure that the angle of rotation is 82.86 which is close to the rotation during anticlockwise inflation. This means if assembled together, these actuators would be roughly symmetrical in their rotations. In addition, this shows that the shape of the actuator is stable and stiff enough to not be affected by the gravity despite it being able to possibly deviate the bending direction.

3.2. 3D print manufacture

The 3D print manufacture involved manufacturing the designs from figures 8, 9, 10 and 16. In order to design them the stereo lithography process was used [10]. It is a liquid based process that builds objects directly from CAD software in STL format [10]. As such, the designed parts from Solidworks were uploaded in STL format to a 3D printer. The resultant products were made of ABS material which has a high stiffness and high strength.

4. Control system and electronics.

In order to drive the actuator, the circuit had to be designed. The following figure shows the schematic diagram of the circuit

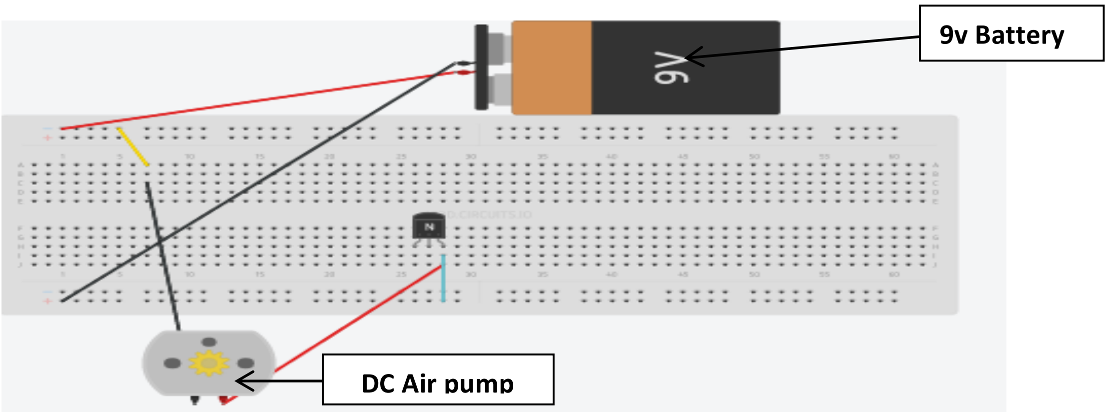

Figure 34. The schematics of the constructed circuit.

The figure above represents the simple circuit for the soft rotary actuator. Since the goal of this report is to develop a part of a robotic system which is the rotary actuator, the circuit is deliberately made as simple as possible. This facilitates integrating the actuator into any robotic system because of its' simplistic control, low weight and low cost.

Figure 35. DC Air pump [11]

Figure 35 shows the DC air pump. This pump is connected to the circuit using the positive and negative pins on its back that have wires soldered on them. It supports voltages up to 6 V with maximum 6psi pressure [11], which is its limit and at that point it drives the actuator rapidly. However, it does not have the inlet/outlet valve which would allow using the pump endlessly and would actually facilitate the inflation/deflation control of the overall system.

5. Future improvements

Due to the problems that were discovered in every stage of the project, there are several improvements that were cogitated to enhance the performance of the rotary actuator.

As was mentioned in section 4 of the report, the circuit was designed in unpretentious manner. However, to increase the controllability of the actuator, several steps could be taken.

The DC air pump in the project does not have an inlet/outlet port that would allow external air to enter the pump. As a result, it was problematic to reverse the polarity of the pump that would deflate the actuator. However, if two pumps like that are used, then it possible to control the inflation/ deflation timing of both soft actuators from two sides of the rotary actuator. For example when one actuator is inflated, the pump corresponding to that actuator is positive. At the same time the polarity of the other pump will become negative, deflating the second actuator by the same amount as the inflation of the first actuator. Such pump is shown in figure 36.

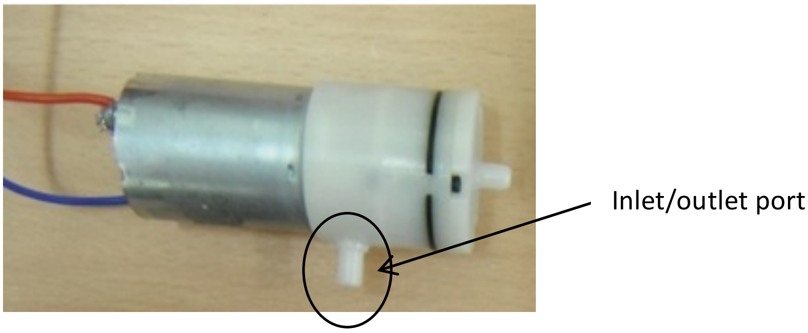

Figure 36. DC pump with inlet/outlet pump [12]

In order to control the angle of rotation, the pressure sensor can be used to sense an increase or decrease in pressures of soft actuators' internal chambers. Sensors such as the ASDX silicone pressure sensors are ideal for pneumatic controls since they are designed to work with non-corrosive, non-ionic working fluids which air is [13]. The operating voltage of this sensor is 0-6V[13]. In the experiment, the soft actuator was properly inflating when the pump was only supplied 6V of power which makes ASDX sensor ideal for the current project.

It was pointed out that, the wiring around the actuator affects its' bending moment since the windings restrict the radial expansion. In order to make rotation more stable and achieve higher rotation as a result, it is essential to decrease the thickness of the walls of the actuator which would increase the capacity of its' internal chambers. As a result, the rotation will be greatly improved. The windings around the actuators should be made more even leaving similar gap between each consecutive winding gap. This would result in angles higher than 90 degrees.

6. Applications

The application of stiffness controllable soft rotary actuators can be extensive. The main goal was to design a pneumatically driven rotary actuator that can be safe for human-robot interaction. Since the actuator is made of silicone material, it ensures safety when people interact with it in terms of, for example, contact.

Possible applications for this technology would include integrating with robotic systems. An example of this is the 7 degrees of freedom robotic arm that has pneumatically driven artificial muscles [14]. During accidents, the rotary actuator can be quickly degassed and worked on since it would be safe for interaction unlike electrical actuators that can deliver a current pulse in point of contact if precautions are not considered. For example, if during accident, the robots are not shut down, then if a person operates on the robot he can receive a shock from electrical motors. However, with soft actuators made of silicone, this is not possible since silicone is not current conductive and if the system is not shut down, a person will not be harmed when coming in contact with the actuator.

In medical field, soft robots are used extensively. For example, STIFF-FLOP project where they created a miniaturized soft robot for minimal invasive surgery [15]. The soft rotary actuator in medical field can possibly be inserted into human organism without contaminating it since silicone is harmless.

In space industries, soft rotary actuators can be used as part of a system in order to deliver payloads to space stations which reduce the weight of the payload since the silicone actuator has a low weight in comparison to commonly used electrical actuators. In addition these actuators can be used in rough terrains due to them being compliant.

7. Conclusion

The stiffness controllable soft rotary actuator was designed to be able to operate at a full range of 180 degrees. However, upon manufacturing, it was realized that the actuator would only rotate by maximum 82.6 degrees where it was stable during the whole inflation. The possible improvements that were suggested involved even winding of the threads around the soft actuator, introducing DC pump with an outlet valve to be able to reverse its polarity and using ASDX silicone pressure sensor in order to have a better control over the rotation of the actuator. The possible applications of this actuator can include the integration with robotic systems in space, medical and industrial fields.

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