Mammal Inspired Legged Soft Robot

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DECLARATION

This report entitled

Mammal Inspired Legged Soft Robot

Was composed by me and is based on my own work. Where the work of 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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Signed: ....

Date: ....

Abstract

This project investigates a proof of concept approach to the design of a textile based leg that is primarily uses easily available techniques and materials. A linear actuator using the transformation of an object from a 2d area to a 3d volumetric object is investigated and tested to produce an operational leg that is used to create a hexapod robot. The limitations and strengths of this type of leg are discussed, with possible gait patterns, actuation steps, and problems/solutions encountered when developing such a leg. The leg demonstrates clear advantages with regard to simplicity, ease of manufacturing, and low price, however there are limitations with regards to the materials used in this given they were chosen based on availability rather than optimal properties. These materials were sufficient to demonstrate a working hexapod robot with a tripod gait pattern to minimise the number of regulators used to only 6, and creating a robot that can achieve an almost %50 reduction in its height and therefore external volume by deflating the legs.

List of Acronyms

EPDM refers to the material Ethylene Polypropylene which is a type of synthetic rubber.
Foam-Core is a paper faced foam board consisting of a polystyrene sheet with paper on the outward facing sides.
Gait ”is a sequence of leg motions coordinated with a sequence of body motions for moving the overall body of the robot” [1]
Legged hexapod robots are ”programmable robots with 6 legs attached to the robot body” [1]
Zip-tie and cable-tie are used interexchangably throughout this report but are synonyms for the same product.

CONTENTS

I. INTRODUCTION

”Legged robots present significant advantages over wheeled and tracked vehicles because they allow locomotion in terrain inaccessible to these traditional vehicles”, with their limitations being ”slow speed, difficult to build, and need complex control algorithms” [2]. Other words used to describe them are ”heavy” and ”large energy consumption”. The design produced in this project aims to tackle these problems by providing a design that is cheap, easy to build, and passively compliant, negating the need for a complex control system.

II. AIMS

The aim of this project is to create a mobile legged robot platform utilising soft robot legs. The legs were designed to take advantage of the compliant nature of a pneumatic system in comparison to a traditional rigid system to navigate rough terrain. The system should be able to move forward without requiring complex control systems or feedback, with the stability and compliance being passively integrated into the design and materials. The goal of this project is to design a low cost and simple alternative to complex robotic legs that can be manufactured with minimal cost and skills required. The finished product was aimed to be able to carry a load to compete with rigid robotic systems in terms of performance while minimising the cost. Within the field of soft robotics, most technologies cover silicone/extensible materials when designing soft robotics which are relatively fragile systems that are prone to damage under real-world conditions. An alternative to this that has been explored is the use of inelastic but flexible materials such as fabrics to create soft robot actuators, which also enables pressure control of the actuator, therefore allowing for variable stiffness legs. The stiffness of the leg can be modified dynamically by controlling the airflow into the leg, therefore allowing it to dynamically adapt to different terrain properties. A high stiffness joint may be ideal for a relatively smooth surface, while a less stiff joint may perform better under rougher terrain conditions as the leg can deform more around the environment.

III. DESIRED MOTION

To achieve the desired walking motion, the stages necessary to take a step forward were studied to be as shown in figure 1.

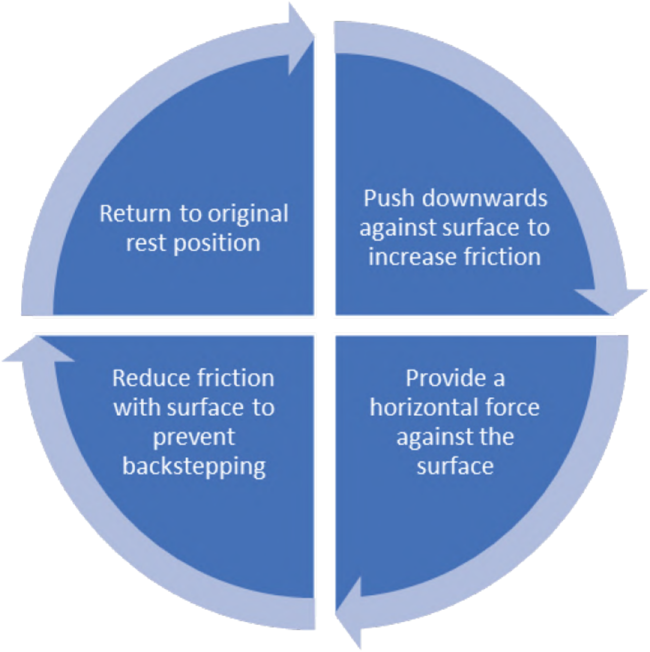

Fig. 1. Diagram illustrating the key stages to moving forward using a legged design. In order for a leg to move, it first needs to provide a force against the surface to increase the normal force. This increases the friction and allows the robot to then apply a force against the surface which applies a force to the robot opposing its force parallel to the surface. This pushes the body in a set direction. In order to maintain this movement as a net movement, the system would need to decrease the friction against the surface before returning to its original state. This is often done in legged systems by pulling the leg upwards and away from the ground before returning to its original state, however alternative methods of decreasing the frictional force are still applicable.

Early on in the project, the ability to bend and then contract away from the surface was determined to be the most difficult aspect of the design, as it requires some degree of control, whether it be through passive or active control mechanisms.

The materials and actuators present within the field of soft robotics also presented constraints when the leg and movement methods were considered. Within the area concerning legged robots, hexapod walking robots benefit from their lower impact on terrain, which is key in environments such as mind fields or environmental/historical studies [1] [3]. They also benefit from more stability and larger payload capabilities than quadruped robots due to their increased points of contact with the ground and higher leg count, but do not suffer the limitations of robots with more than 6 legs where the stability benefits are negated [4].

The diagram in figure 2 illustrates the different types of legged hexapod robot designs. The leg design seen in mammals was chosen as inspiration for our system. This layout uses legs that are perpendicular to the surface with a knee joint along the approximate middle of the leg that will bend backwards/forward. Linear actuators are easily manufactured using fabrics are linear actuators, with a pneumatic cylinder being able to provide the most stiffness in the central lengthwise axis. By using this design I would be able to place the actuators below the platform, therefore maximising the strength of the inflatable legs. This configuration also requires less energy to move than other legged configurations due to its [1]. The use of an inflatable chamber will mean our main chamber/leg will be a variation of a cylindrical inflatable chamber that provides a space to be inflated. The alternative bio-inspired legs seen rely on rotation around the central axis of the leg which is difficult to achieve using inflatable actuators. These systems often have the legs extend beyond the body horizontally, which would introduce forces perpendicular to an inflatable chamber’s length. This would require extra reinforcements as the force vertically would be exerted on the body through tension along the side of the chamber. Otherlab’s Pneubotics department developed an inflatable walking robot as seen in figure 3 that uses an inflatable hexapod robot that also uses textile based actuators and chambers at a much larger scale, with the legs being placed along the side of a central chamber. The robot relies on 4 muscles along each leg to achieve motion and can only achieve small steps due to the limited bending provided by its actuators, which limits its maximum speed. The design produced by Otherlab primarily focuses on maximising the load capacity rather than manoeuvrability and speed which is one goal of my development Tedeschi (et al.) discusses that the mammal based legs are the least stable form of leg system due to them being higher up, but that complexity would be overcome by designing our robot to be passively compliant [1]. The leg orientations seen in the figure (2 are illustrated using discrete joints, while the leg developed will use a continuum leg mechanism with the ”same orientation” joint configuration.

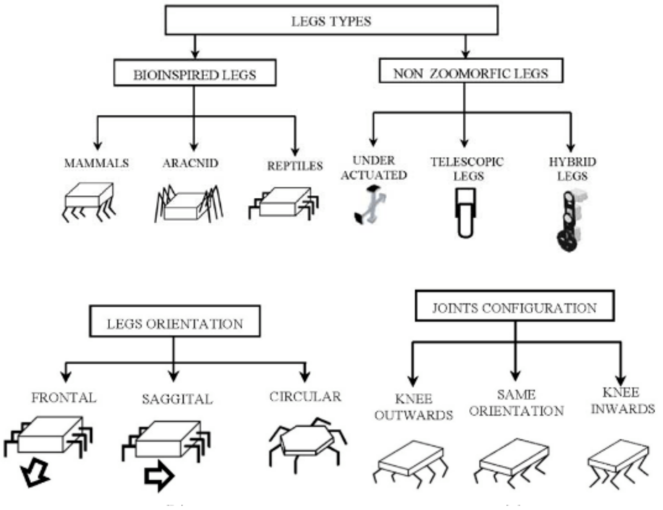

Fig. 2. Diagram illustrating kinematic models of different types of hexapod robot leg types, orientation and joint configuration. Figure from [1]

IV. Approach

A. Single Input Leg

To start off with the project was approached with the idea of simplifying the design of an actuator that can move forwards, and aimed to have a leg that could achieve forward motion utilising only one input with a passive structure that allowed it to achieve the desired motion specified in fig 1. During the development of this idea, multiple designs were tested. A working design developed is seen in figure 4 which was capable of providing a forward movement by utilising rapid inflation of the system and slow deflation. The rapid inflation caused a sudden jolt that exceeded the the resistive force provided by the elastic material along the direction of airflow internally. This caused the material to leg to expand directly downwards, before the force due to airflow had balanced out, causing the elastic to cause bending. This bending at full extension provided a force backwards. The system is then deflated in a pattern that relies on the elastic strips, which avoids the issue of repeating the motion through inflation and deflation. While this worked, it was very difficult to get repeatable results and lacked the control desired.

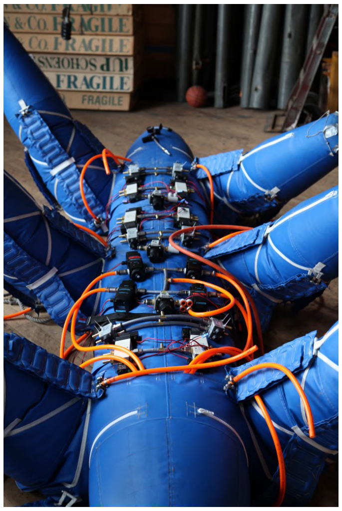

Fig. 3. Image showing the bottom of Otherlab Ant-Roach design that uses 4 linear actuators per leg placed at right angles around the length of each leg. The project is designed to maximise the carrying capacity of a pneumatic structure and uses frontal and forward facing joint configurations that are placed at a diagonal to the surface to increase leg span [5]

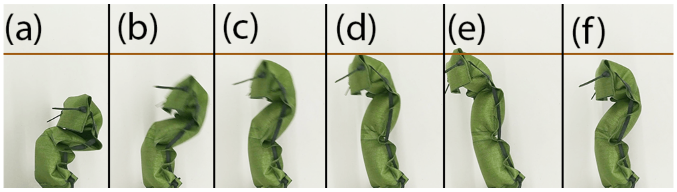

Fig. 4. Figure showing a single input leg developed by Hareesh Godaba. The leg design relies on the relationship between the elastic and the speed of the pressurisation. The leg shows the inflation of the leg from an non-inflated state (a), to fully extended (d), at which point the force due to rapid pressurisation equalises with the elastic causing the actuator to bend backwards as seen in (e). The deflation follows the elastic causing it to move downwards without reversing the motion, therefore causing forward motion. The brown line is used to indicate a hypothetical ground level. This actuator was also tested by placing sheets of paper and fabric underneath. Inflation and deflation of the leg pushed the object backwards therefore proving that the leg is capable of preforming the stages of taking a step.

B. Actuators

During the testing phase I was experimenting with various designs that used the in-extensible properties of fabric to achieve bending such as the example seen in figure 4. While striving to achieve more control, the linear contraction actuators seen in figure 5 which are described in detail in section V-A1 were particularly interesting as they allowed me to design a system similar to the operation of a muscle. This was used to develop the mammal inspired leg seen in 9 which consisted of two contracting actuators on either side and a main inflatable chamber. This configuration provided small amounts of bending due to the chamber providing a stiff joint. 2 small stitches were sewn perpendicular to the chamber length underneath the actuators to provide a more localised bending location. Implantation of the localised bending caused the actuator chamber to behave more like a discrete system as all the bending was occurring around this stitch with the chamber remaining relatively cylindrical with little curvature on either side. The effect of this can be seen in figure 7, where a higher bending angle was achieved at the cost of the rigidity of the main chamber. In both designs, contraction of both chambers simultaneously provided contraction of the main chamber along its length. This caused me to explore the idea of using 2 extra actuators along the left and right side of the leg that would be connected to a common input and provide control of the length of the main chamber. This ultimately was not necessary as control of the main chamber pressure proved to be sufficient for decreasing the contact area/force, and therefore decrease the friction against the surface.

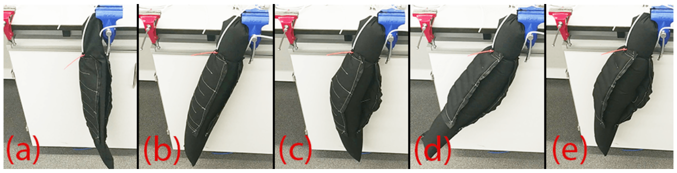

Fig. 5. Images showing initial mammal prototype leg, utilising 2 individually controlled linear actuators on each side with a cylindrical middle section. The diagram shows the leg in all of its states, with (a) showing it while deflated, (b) showing it while inflated, (C) showing the right actuator contracting, (d) showing the left actuator contracting, and (e) showing both actuators contracting simultaneously resulting in shortening of the main chamber length.

Fig. 6. Image showing the horizontal stitches placed on the actuator design seen in figure 9. These stitches cause the chamber to separate into two cylinders that are connected via a section of minimal expansion which causes the stitch to act as an axis of rotation in a leg design comprising of two rigid cylinders and an actuator. The addition of this stitch results in the increased bending seen in figure 7

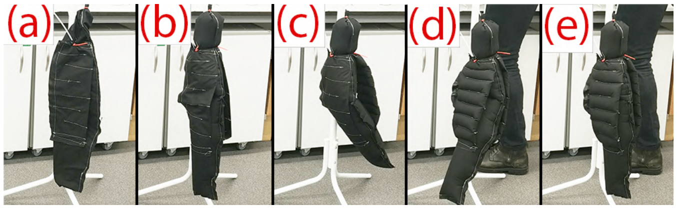

Fig. 7. Figure showing the same leg seen in 5, with 2 added stitches as described in figure 6 which create a discrete axis of rotation/bending. This results in more defined bending of the middle chamber as it bends around the seam as a joint rather than a continuous bend as seen in figure 5.

V. DESIGN

The final design is a hexapod robot, using a 2x3 configuration of legs. The legs use soft robotic actuator principles and are pneumatically driven. The legs are attached to a primarily foam based body which allows for a lightweight frame that contains the pneumatic actuators and control circuits needed to drive the system, while providing mounting and support for each of the legs.

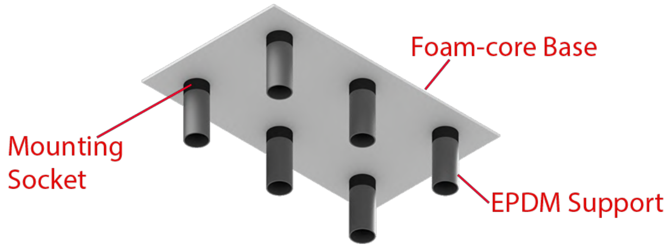

Fig. 8. Rendered CAD model of the base frame, showing a foam-core sheet with 6 mounting positions for the legs, EPDM support, and rigid polyurethane foam mounting sockets.

A. Legs

In this robot there are 6 legs that are manufactured using easily available and low cost materials and techniques. The leg consists of 3 parts, the 2 pneumatic actuators and the structural chamber. The outside of all 3 parts is made from a 100% Polyester Waterproof Coated Micro-fibre fabric. This material provided the in-extensible outer shell needed to allow for pressure control of the system.

1) Actuation: The actuators developed are made out of a piece of fabric folded and stitched as seen in figure 9. The actuator created allows for linear contraction when inflated along its length. The muscle actuates by deforming from a flat area (2D) to a cylindrical volume (3D) in areas that are defined by the stitches. Keeping this in mind, once could possibly model the contraction behaviour given the surface is relatively in-extensible so surface area can be assumed to be constant. With the current design size, different numbers of stitches at various spacing were tested to find the ideal with the results seen in table I. The ideal stitch count was determined to be 5 with a contraction of 23% the original length. This is lower than the theoretical calculated maximum of 33% which could be due to factors such as the fabric bending geometry or the measuring method which included sections of the actuator that were not key to the actuation and were excess fabric for easier mounting to the main leg chamber.

The actuator operates by utilising the geometry between surface area and volume. Given the surface area is relatively constant in an in-extensible material, we can modify the geometry of the material in 3d to control the ratio of material within the 3 dimensions, which results in a decrease in length along its 2d axis as the material is used to achieve the larger curve needed as seen in figure 10.

The designed actuator was also tested to see its ability to apply force during contraction by securing the actuator to a

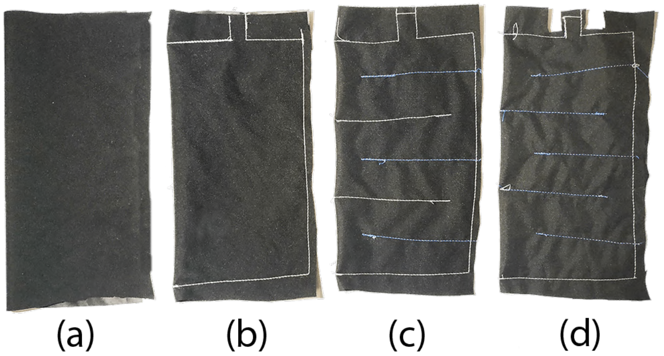

Fig. 9. Diagram showing the steps needed to manufacture the actuators for the legs. Picture (a) shows a piece of 220mm x 210mm fabric folded in half along its longer length, resulting in a folded piece 110mm x 210mm. The shape seen in (b) is sewn onto the fabric. This creates the pneumatic chamber with an inlet at the top. This is followed by the horizontal 5 lines seen in (c). These provide the chamber with a more controllable direction of inflation. An area next to the inlet section is cut out to allow for the easier fixing of the tube through zip-ties while maintaining an easy method of mounting the actuator onto the leg.

TABLE I
TABLE SHOWING THE NUMBER OF HORIZONTAL STITCHES ON THE ACTUATOR VS THE LENGTH UNDER INFLATION

Number of stitches	Length when inflated (mm)
Non-inflated	210
0	210
2	180
4	175
5	170
7	190

vice from the top, and attaching a mass to the bottom as seen in in figure 11. The test showed that there is a linear relationship between the leg's bending capability and the resisting force. This could mean that the leg may not be able to achieve the same step size at different loads which could complicate control. A hypothesis on the results viewed is the lack of air-tightness in the chamber and the fabric's weave which could mean that the actuator has a terminal pressure at which increasing airflow would result in increased leakage. This capability could be increased by creating an air-tight actuator with materials capable of handling higher pressures, as well as stronger stitches which were the first point of failure at higher pressures.

For manufacturing, the two actuators are sewn onto the middle chamber while it is still a single sided rectangular sheet of fabric before the rectangle is folded and stitched along the sides to create the middle chamber as described in section V-A. The two actuators are attached to the leg at 70mm from the top as seen in figure 12.

2) Leg Body: The two actuators in the leg surround a structural chamber which provides the section that is affected by the contraction from the legs and provides the compliant interaction with the surface. To achieve this various chamber designs were tested and a cylindrical chamber with a conical tip was determined to be the ideal geometry due to it providing the most surface area and and increasing surface area as the material deflates/experiences a large force, which causes this leg to passively adapt to its surface in relation to its weight, and vary contact area through pressure. During initial testing, the chambers were tested without an internal bladder which provided quick inflation and deflation, however for the final design an oversized High Density Polyethylene chamber was used to provide an air-tight bladder. This air tight bladder decreased the pressures required to inflate the system and allowed the legs to achieve higher internal pressures, therefore achieve higher stiffness and increase maximum load. The oversized chamber was used as it ensured that the internal bladder would not increase the Young's modulus of the leg, as the outer chamber is able to slide freely along the relatively low friction of the Polyethylene bladder, and the oversized nature of the chamber for inflation while the fabric outer shell provided the in-extensibility, shape, and protection against the surface. The bladder is secured around the socket in figure 17 using zip-ties. the fabric outer shell being secured surrounding that on the mounting socket using zip-ties, as seen in figure 18.

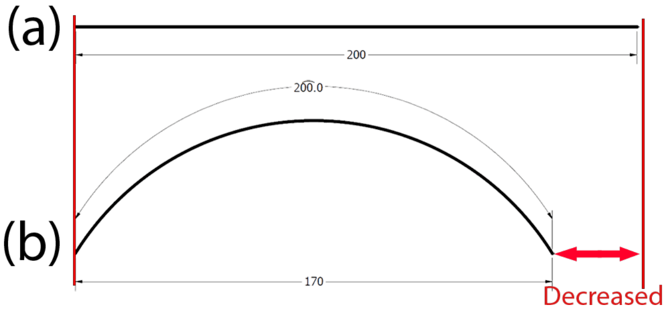

Fig. 10. Diagram illustrating the theory behind the actuator's operation. Figure (a) shows a flat surface of 200 mm which we can associate with one side of our fabric in an non-inflated state. When inflated the material balloons upwards as seen in (b). Given the material is in-extensible, the ballooning results in the surface to arc which results in a shorter distance along the length of the actuator as the material must maintain its constant surface length of 200 mm. In the designed actuator this ballooning effect occurs in multiple smaller ballooning rather than one large ballooning as it provides more reliable and larger contractions as proven by the tests in table I.

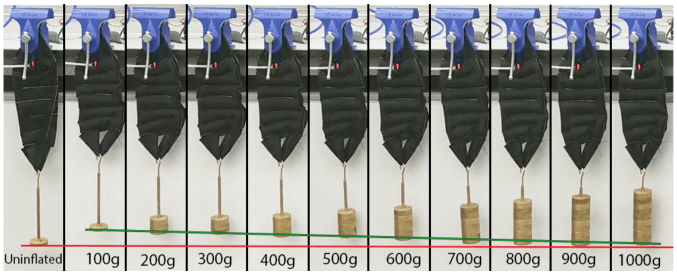

Fig. 11. Test of a single actuator's ability to exert a force. The actuator were tested by deflating the actuator, adding a weight to the bottom and inflating the muscle until contraction reached the maximum. This process was repeated with increasing weights by 100g increments up to 1kg. The test allowed me to discuss the limitations of the actuator in its current form without supply pressure being the limiting factor. The red line indicates the position at a non-inflated state, while the green line shows a line of best fit of the height achieved, which shows a linear relationship between the weight and the extension.

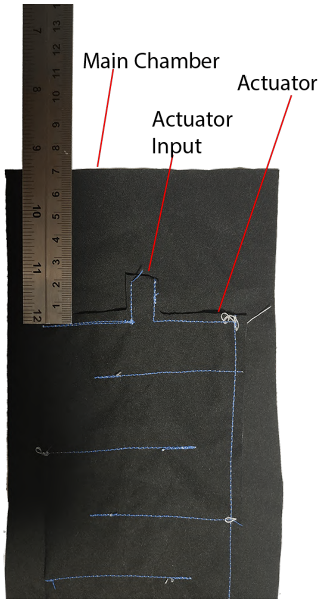

Fig. 12. Image showing the placement of the actuator along the fabric rectangle 7cm from the top. This rectangle is the edge of the part that will become the main chamber as seen in figures 14, 15 and 16. The actuator is fixed to the main chamber along its top and bottom using a sewn seam. This is done before the fabric rectangle is turned into the main chamber.

B. Main Chamber

The body of the contraption is designed to provide structural support for the legs by providing a place to mount them, and used to house the electronics and pneumatic pumps. The base designed consists of two parts. The first is the mounting and control section which will have the electronics, wiring and legs attached to. This section is made from a foam core sheet that has 6 circular Polyurethane foam sockets adhered to the bottom. At the middle of each circular polyurethane socket is a 4mm hole passing all the way through both the socket and the foam-core base. This part can be seen in figure 8. This is used to secure a 4mm pneumatic tube using adhesives. The second half of the body provides structural rigidity and protection, and reinforces the leg joints. This structure is primarily made from a sheet of 25mm Rigid Polyurethane foam that has holes drilled out to allow the legs to protrude from. The base would slide into the protective structure after the individual legs are fixed onto each mounting socket. These materials were chosen due to their low density and high rigidity, which allowed for the creation of large sweeping frames that can support the legs while minimising the weight of the body itself. Originally, the design relied on the pressure of the legs with minimal internal support for the legs, but testing revealed that the legs did not provide sufficient rigidity during inflation/deflation to maintain their direction of inflation so an internal tube of rolled up Ethylene Polypropylene (EPDM) sheet was used as seen in the CAD model seen in figure 8 and the final model seen in 17 . This material is a form of artificial rubber was chosen due to its low density and high flexibility, and ability to withstand the temperature of hot glue which was used to affix it to itself and the frame. The flexibility is key as this support is designed to provide a more directed inflation while maintaining the joints ability to bend. After using this a large improvement in stability and the ability to inflate to its desired neutral state from no air, though it does add some thickness to the design.

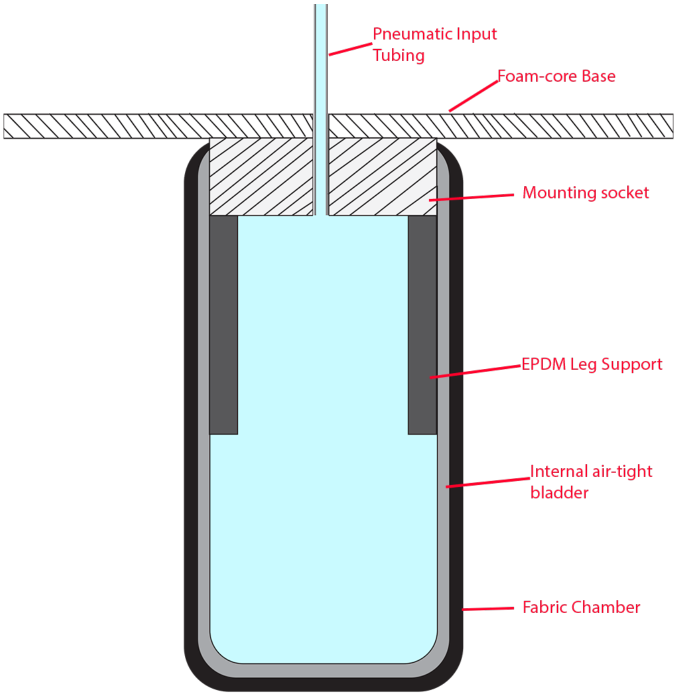

Fig. 13. Cross sectional view of the leg chamber and how it's attached to the base through the mounting socket which is glued to the foam-core base. The supporting foam is a hollow tube made from 5mm Ethylene Polypropylene (EPDM) sheet material. This provides support for the leg by ensuring it expands in the right direction. The mounting socket is made from High Impact Polystyrene. This tube is fixed to the mounting socket through the use of a glue adhesive.

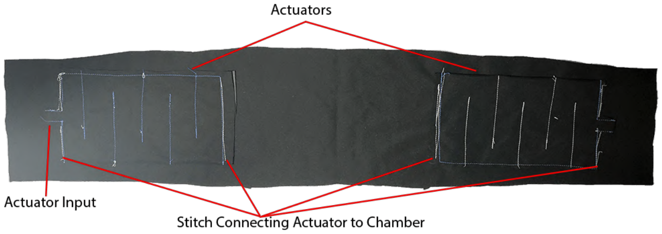

Fig. 14. Image showing the entirety of the fabric rectangular section with the two muscles which will be folded in half as seen in figure 15 to form the leg chamber .

During early testing, the main chamber was seen to have very little friction with the surface so a small strip of 2mm thick EPDM was added to the tip of the leg which provided the necessary friction against the surface. This also provides extra protection against the surface by providing padding in areas that would experience a large amount of friction.

C. Materials and Manufacturing

Throughout the design of this project, one of the key considerations when choosing parts/materials was availability of the material and the ease of manufacturing. This was to allow the system to be easily reproducible. This influenced choices such as using a commonly available Micro-fibre Polyester fabric

Fig. 15. Image showing the steps to take the fabric section seen in 14 and produce the leg. The fabric square is folded in half along its length, with the actuators facing inwards. A seam is sewn along the edges of the material that curve inwards from either side towards the middle bottom as seen in (b). The excess material is then cut, and the chamber is folded inside out as seen in figure 16.

Fig. 16. Diagram showing how the leg is folded inside out after figure 15 from the internal side that the stitch is located on, through the bottom (b)(c), revealing the micro-fibre side (d) with the actuators externally located. The actuators need to be outside the chamber as they are able to provide more contraction by increasing the bending moment through increased distance from the centre. This also increases bending as the contraction has a horizontal component as well as a vertical one, while contraction internally would act primarily by shortening the fabric through a force parallel to the length.

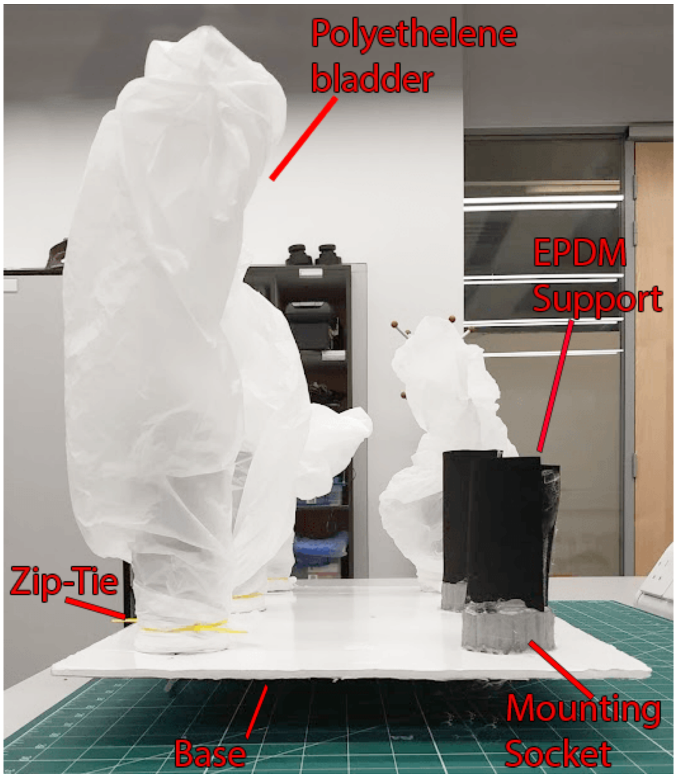

Fig. 17. Assembly of leg, with and without the air-tight bladder, showing the foamcore board base with the rigid polyurethane foam socket, with a EPDM support on top on the right. On the left, the Polyethylene bladder attached to the foam socket using zipties is visible.

that can be acquired from most fabric suppliers, and can be substituted with any other material with similar in-extensible properties. The base was designed to be manufactured using sheet material primarily due to its availability, with materials such as 5mm Foam-Core sheets and Rigid Polyurethane foam sheets which are available from craft stores or en mass from dedicated suppliers. The high density polyethylene bladder used to provide air-tightness was made by acquiring plastic bags that are commonly available in grocery stores, and cutting any excess material to create a chamber that could be fixed to the leg. While not perfectly air-tight, the bags provide good pneumatic qualities and are able to deform and fit inside the fabric within the necessary pressures due to the force required to contain the pressure being provided by the fabric shell. To ensure that the polyethylene bags do not experience pressure, there was excess material inside the leg which allowed it to adapt to deformations without experiencing any stress. The low friction between the bladder and the fabric meant that it could slide against the surface as it expands. The EPDM cylinder used to provide the support was made from EPDM sheet material which is available in most hardware stores due to its common use as a roofing material.

The legs and actuators were all manufactured by manually cutting the fabric using scissors and sewing by a commercially available Brother LS14s stitch sewing machine. While this may introduce error by variety when the cutting and stitching is concerned, it allowed for quick prototyping and manufacturing, and the compliant nature of the system is able to operate regardless of this variation. Straight stitches were used for all sewn parts.

The use of these materials for the design of an actuator provides a clear advantage over the more traditional robot actuators within both rigid and soft robotics which rely on bespoke parts that increase the manufacturing and material cost.

The disadvantage of these materials used is they may not be the ideal materials for the use case described and thus the design may be inefficient because of this. Other disadvantages are the current frame design is not water resistant and may dissolve if it encounters water

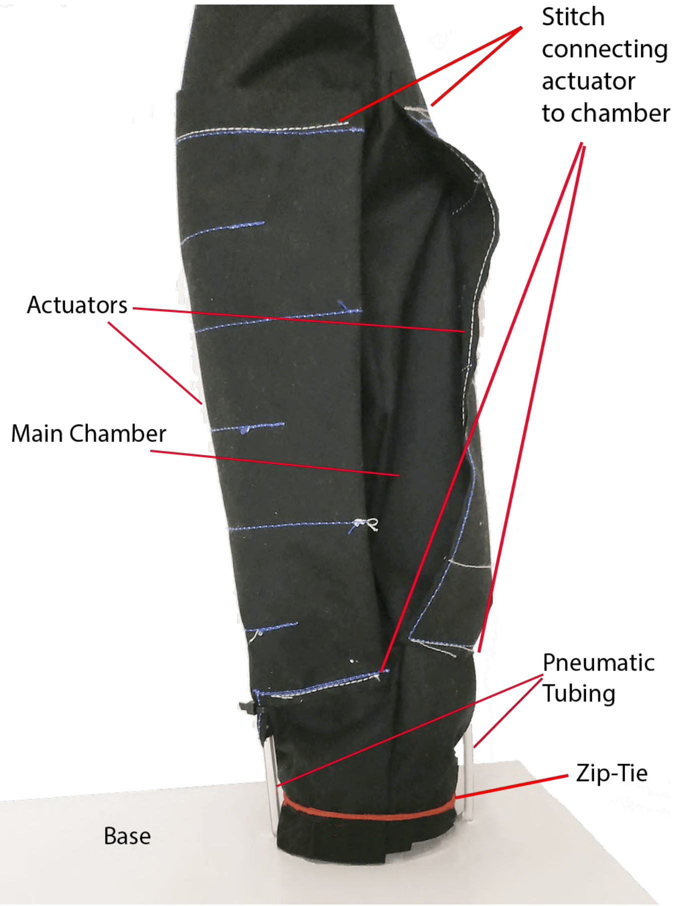

Fig. 18. Leg after the fabric outer shell has been placed onto the bladders seen in figure 17, with the actuators facing forwards and backwards. The fabric is attached by zip-tying the bottom to the socket Below where the bladder attachment zip-tie is located. The two pneumatic tubes for the two actuators are secured via zip-ties inside the forward/backward actuators, with the tubing going into the sheet via holes located in the foam-core base.

VI. Control

The design specified has 24 pneumatic inputs. Three per leg - 2 actuators for forward/backward bending and one to control the main chamber. To control this system we had six pneumatic valves to provide control. These six outputs were connected to three way pneumatic splitters, creating six groups of control. This was done by separating the legs into two groups of three, one group comprising of legs 1,3,5 and the other 2,4,6 (as seen in figure 20. These two configurations were called the ”Right” group, and the ”Left” group, in relation to the location of the majority of the legs (Right: 1,3,5 , Left: 2,4,6)

A. Motion

The robot was capable of walking forwards by following the steps seen in the flowchart in figure 19

B. Pneumatic Systems

The pneumatic part of the section consisted primarily of 4mm diameter pneumatic tubing. This tubing was cut to length as required, with 4 way pneumatic push splitters being used to connect and split the airflow between different sections of the robot. For this robot, 8 four-way splitters were used and 1 Y splitter was used. These were used to construct the system seen in figure 22. The splitters allowed me to use 6 regulators to control 24 inputs, and only require one output for pressure into the system that is distributed throughout the system. The pneumatic splitters and regulators are housed within the robot body with one pneumatic tube exiting the system that connects to a compressor.

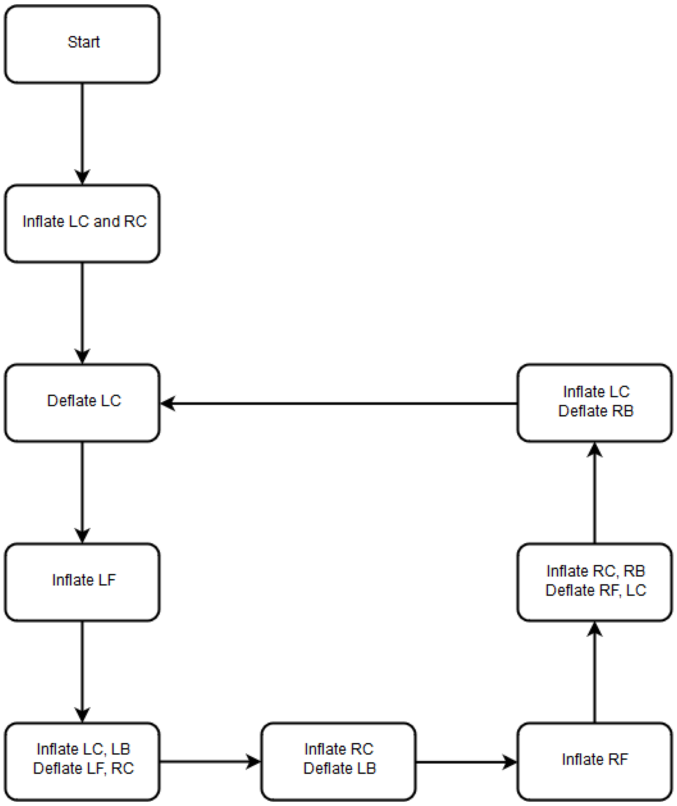

Fig. 19. Flowchart showing the steps needed to walk forwards, where the L and R refer to the side with the majority of regulators, and the C F B corresponds to centre, forward actuator, backward actuator respectively

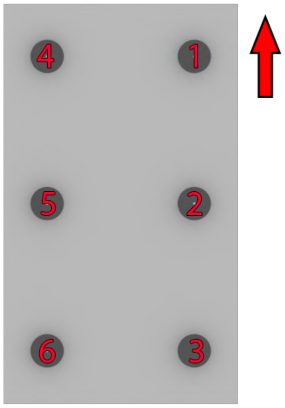

Fig. 20. Diagram showing the label used to refer to each leg, with an arrow indicating the directional front of the robot.

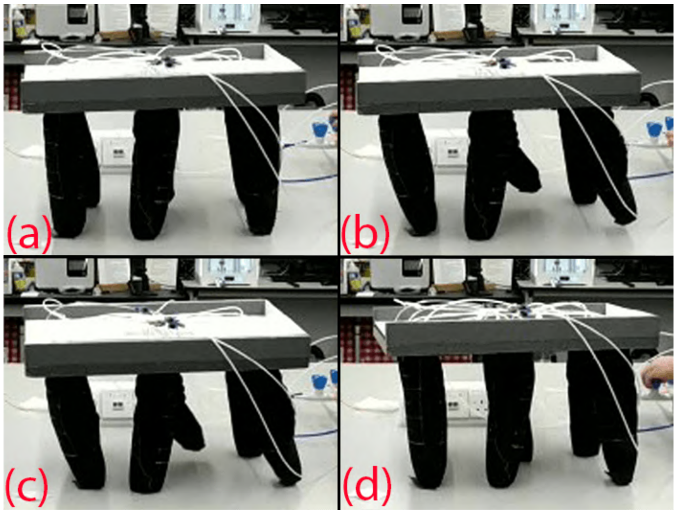

Fig. 21. Diagram showing a single step for the robot. (a) shows the starting stage of the robot with all 4 legs parallel and fully inflated. The robot deflates the set of legs and inflates the forward muscles for those legs as seen in (b). The platform then inflates the middle chamber for the legs, resulting in (c) where the bent legs are making contact with the surface. The forward actuators are deflated and backward actuators inflated resulting in (d) where the robot has moved forward by one step .

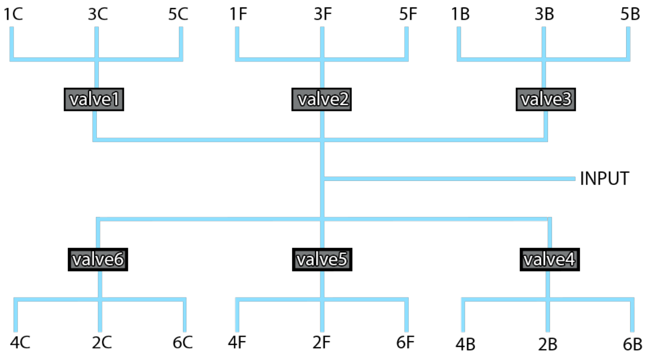

Fig. 22. Diagram showing how the pneumatic systems were connected to the legs, with the blue connections indicating the airflow paths (tubing/splitters).The outputs are indicated by a two character combination, consisting of the Leg number as specified in fig 20, and a character indicating the chamber: F for forward actuator, C for main chamber, B for backward actuator.

C. Pressure Regulators

The system uses six SMC ITV0050-2BS pneumatic pressure regulators to control the pneumatic actuators. These pressure regulators were chosen due to their small and compact size (89mm x 15mm x 50mm), and their mass (100g) which allowed them to be placed on board of the system. The regulators require a 24v DC power input which is currently being provided by an external power supply. With all the pressure regulators running the system current was approximately 0.4A. Currently the system relies on a large power supply but powering this system through on board batteries is possible. The regulator has one input signal that can be controlled by varying the voltage between 0v-5v, with 0v providing, and 5v to open and allow air through, with an analogue voltage in between allowing for partial control.

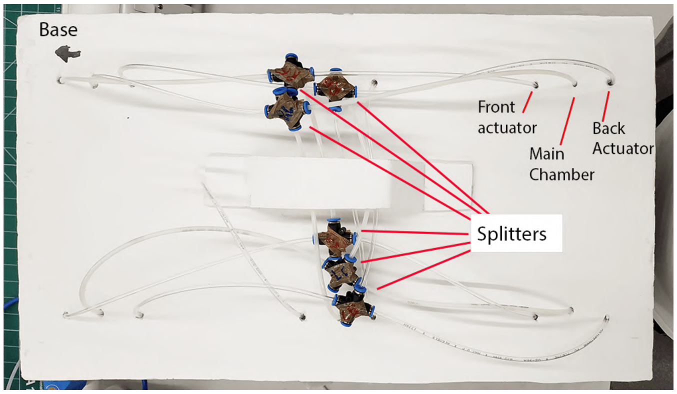

Fig. 23. Image of robot base with six four-way pneumatic splitters connecting to the corresponding control group. In this diagram, each splitter is connected to 3 of the inputs for the legs, with the fourth input left to be used to connect to the pressure regulators. This was used to test the robot without connecting the electronic pressure regulators by manually inflating and deflating different groups. You can also see how the three inputs for each leg were placed on the top of the base board, with the location of each input tube leaving each leg corresponding to the location of the chamber along the leg

D. Power and control distribution

To make the power distribution and the control of the pressure regulators easier, a power and signal distribution board was developed using strip board, which provided screw terminal inputs for the pressure regulators and power, a switch for power, and six pin-headers for easy connection a microprocessor/controller. A protective case was 3d printed for the board as seen in figure 25, and can be seen with the pressure regulators in figure 26.

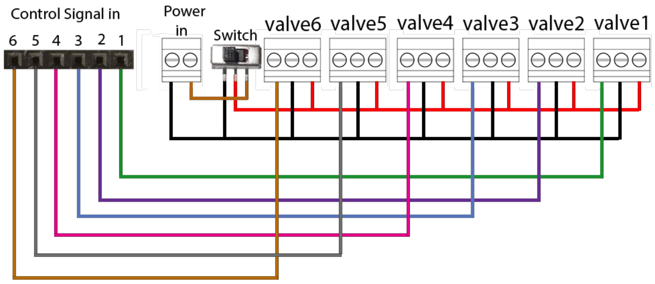

Fig. 24. Circuit designed to distribute power to the pressure regulators by providing a shared parallel connection for all the pressure regulators, and pin-headers for signal input for each corresponding pressure regulator. This is to make connecting all the pressure regulators to power and signal simpler and easier to debug. The inputs for the pressure regulators are labelled with ”valves” on this diagram.

E. Arduino

An Arduino compatible board was used to provide control to the circuit by connecting the pressure regulator inputs from the distribution board to the Analogue pins. This allowed for control of the voltage through pulse-width modulation , varying it from 0v to 5v as is required by the pressure regulators. The microprocessor allowed for this variation by setting an output port to a value between 0 and 255 which corresponded to 0 and 5v.

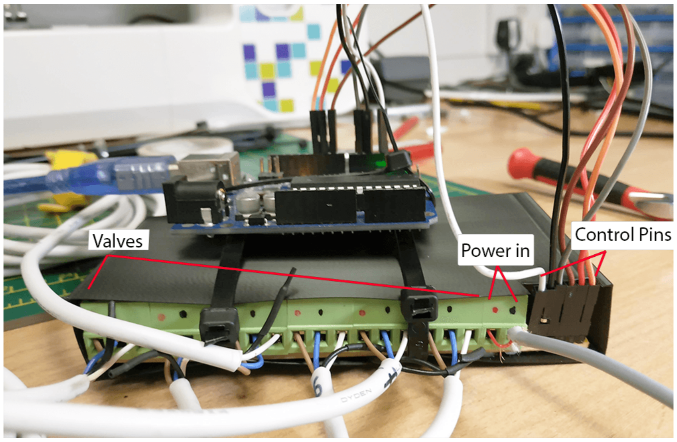

Fig. 25. The circuit seen in figure 24 was made using strip-board. A protective case was designed and 3d printed to protect the circuit and allow it to be easily mounted inside the robot body. The micro-controller can be seen mounted to the top of this circuit using zip-ties

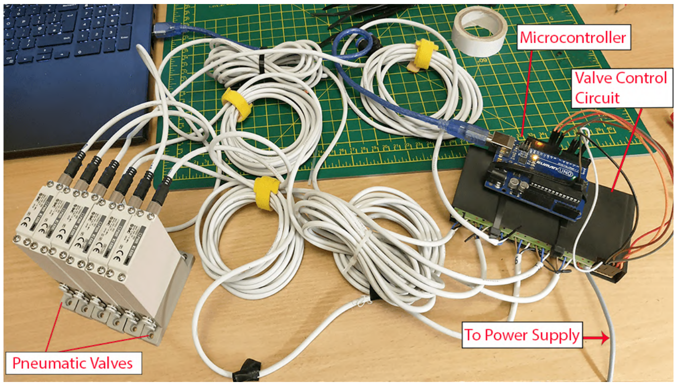

Fig. 26. Completed wiring of the pressure regulators to the distribution board to an Arduino that is being controlled by a laptop. The circuit manufactured in 25 can be seen connected to power and a micro-controller, with the 6 pressure regulators connected to the control circuit which provides power and control. In this diagram the pressure regulators are labelled as ”valves”

VII. MOTION AND STABILITY

The robot stability was tested by applying a force perpendicular to its legs at various points from multiple angles. Initially, without the supporting EPDM, the leg was able to inflate and stand up, but was completely unstable as the legs were capable of bending in any direction without any restriction except for the zip-ties at the top. Another issue that affected stability was the initial design did not use any internal air-tight bladder which stopped the system from reaching a stiff state. After adding the supporting cylinder and the internal bladder, the system was much more stable and capable of inflating into a standing position without requiring any external input/leg tweaking. Initially, any change in the system state would cause the legs to fold and the system to collapse. With the modifications, the system was able to freely stand and withstand reasonable forces without being knocked over. This was tested thoroughly before the addition of the pressure regulators/electronics into the base, which could be affecting the test results as the higher centre of mass would decrease the stability of the robot.

To walk, the tripod gait discussed by Tedeschi(et al.) [1] was chosen as it required the least number of control pressure regulators as the legs are grouped into groups that preform the same functions, having the highest speed over relatively flat ground, and being statically stable at all times. The static stability at all stages is key for the development of a robot that can walk reliably without feedback. Implementation of a feedback loop could open the possibility of using a more dynamic gait pattern that is able to adapt to the environment but for this project the robot is relying on the compliant legs to achieve this.

While moving the components seen in figure 26 onto the board, the components were laid out in a manner that was mirrored along the vertical centre to keep the centre of mass in the middle of the robot. Length wise, the pressure regulators, splitters and power distribution boards were arranged in a way that centres the mass and moving components to ensure it is in the centre for both axis.

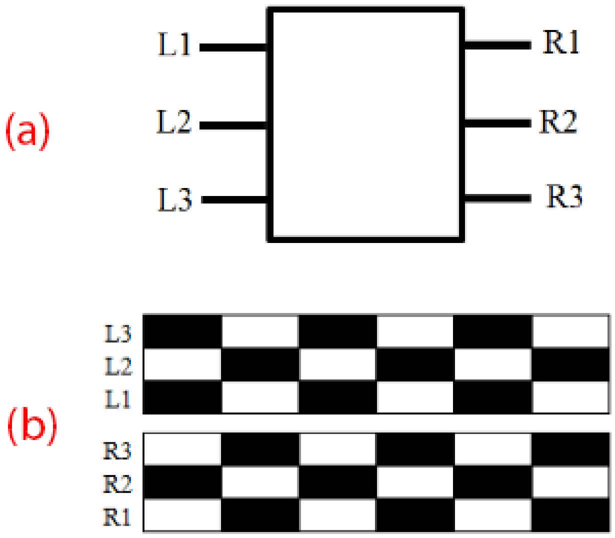

Fig. 27. Representation of the tripod gait taken from Tedeschi (et al.) [1] showing a representation of a hexapod (a) and the timeline of what each leg is doing (b). In the timeline, the white indicates times when the foot is in contact with the ground, while black indicates otherwise. By preforming this stance the system is statically stable due to 3 contact points occurring at all times.

VIII. FUTURE DEVELOPMENTS

Many of the techniques and materials discussed in this report were chosen due to their availability and ability to quickly prototype. These materials and designs may not be the optimal for a future development of the product or entry to market, and thus more research into optimising the material choices and design may be required to achieve optimal results.

Examples of this include:

- The cable ties used to secure the leg and bladder to the robot could be replaced with a method of attachment that provides a better seal and allow for easier removal of the leg.

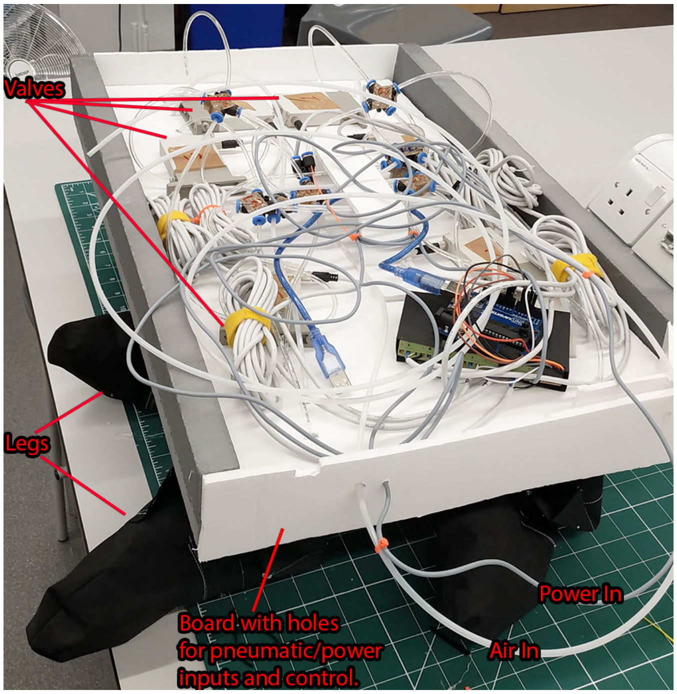

Fig. 28. The image shows the body with an open top, showing the internal placement of the wires and cables, and the addition of a board to the back of the robot base that provides 2 holes for power and pneumatic pressure inputs, and a slot at the top left to allow for the arduino's USB input to be mounted, where a USB extender (female to male) would be able to connect to provide serial input/output to a computer for control or debugging. The pneumatic pressure regulators were secured to the foamcore base using double-sided tape.

- The frame and body design/materials could be optimised to minimise weight and maximise strength, and make it easier to manufacture. This could be through evaluating the structure through CAE software, and using CNC techniques for manufacturing such as laser cutting to provide more accuracy and faster output when manufacturing.
- using a CNC fabric cutter to more repeatably and accurately cut the the fabric pieces for manufacturing.
- Hot melt adhesive is not an optimal method of attaching parts together. Use of mechanical jointing or more suitable adhesives such as spray as 3M Foam Fast 74 Spray Adhesive, or relying less on adhesives and designing the robot to use reusable fasteners such as bolts or clamps to allow for easier repair and construction.
- The use of an inflatable base rather than just legs, and utilising circuits integrated into the fabric may provide a system with a smaller footprint for transport when not in use, that would be able to expand into its full size when needed.
- The dimensions of the robot and actuator could be better optimised for the motion. Currently the spacing of the legs, size and length of legs and the size of the actuators were chosen arbitrarily through guesses based off experimentation and some testing such as regarding the number of stitches. Further study into the dimensions of each part for optimal results would provide with a design that should be able to exceed the capabilities of the current design as the main aim was to provide a proof of concept.
- On board power by using Lithium polymer batteries to allow the robot to navigate without a large power supply given the pressure regulators use 24v at less than 0.5A with maximum load.
- On board pneumatic source using a lighter compressor, or a pneumatic cylinder with a pressure regulator.
- use pressure gauges to measure the internal pressure of each leg to automatically adjust the pressure.
- Use of gyroscopes and accelerometers to check the current orientation of the base and adjust the legs accordingly to maintain balance.
- Use of textile sensors or visual servoing to gain a known model of the status of each leg for more reliable control.
- Explore the ability for the system to move sideways through differential bending of the legs. Explore alternative gait techniques.
- Use more pressure regulators to be able to individually control each input. 24 pressure regulators would be required.

IX. CONCLUSION

The legged robot system developed is a proof of concept that has proven that such a system is capable of walking on a relatively flat surface without much trouble, which is successful at achieving the aims set initially. It does this with an extremely low cost in terms of the structure and actuator in comparison to other soft robots utilising materials such as silicone and moulding, and traditional robots utilising discrete joint systems. The system is also achieving its goal of being easily manufactured with materials and components that are easily available and low cost, with the exception being the parts involved in the control system such as the pressure regulator or the custom power distribution board. In this design, the robot is capable of functioning using small binary valves that are cheaper, lighter and more energy efficient than the regulators for sections such as the actuators, and using a single regulator that would ensure that the pressures entering all the actuators and/or legs are below the maximum threshold. This would therefore lower the number of regulators needed from 6 to 2, with 6 binary valves used for the group control.

In terms of manufacturing, alternative materials and manufacturing techniques could be used as discussed previously to create parts with less variation which would therefore make it easier to accurately model and control. Variation within the legs has caused issues regarding the bending capabilities of each leg, with some legs bending more than others, and some having longer middle tubes than others which caused less points of contact under low loads which fixed itself as more weight was added through moving the electronics and control on board.

The system developed was capable of supporting its own weight with all the electronics on board except for the compressor and power supply as seen in figure 29, reaching a total height of 37cm under full inflation, and 20cm when deflated as seen in figure 30. This is an almost 50% reduction in the height of the fully inflated system which shows a clear advantage for transport of the system as the legs are able to decrease its volume. This can be further improved by decreasing the length of the supporting EPDM tube by evaluating different lengths to find the minimum effective length.

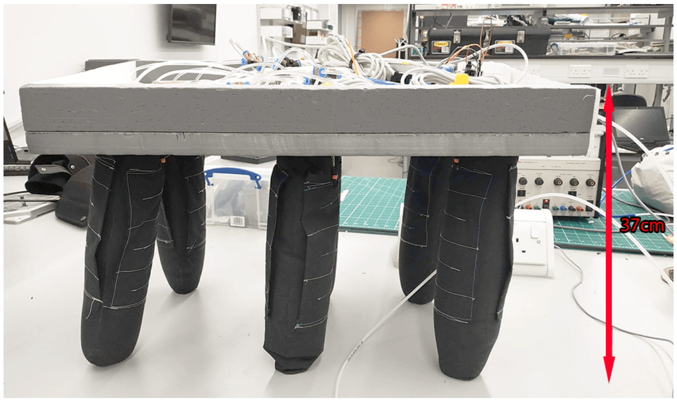

Fig. 29. Image taken from the side of the robot with fully inflated legs and the control circuit on board, showing a height of 37cm.

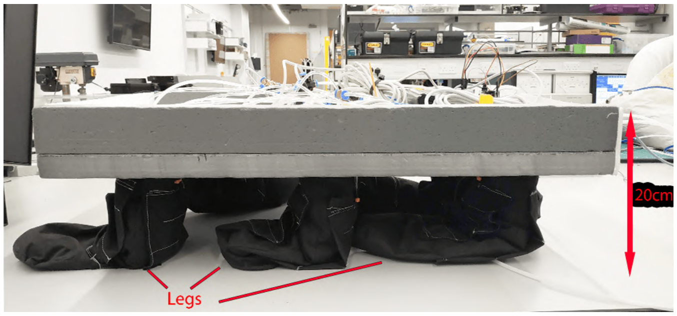

Fig. 30. Image taken from the side of the robot with the control circuit on board, showing a height of 20cm.

The system developed and tested shows promising prospects that require further research into materials, gait, and control techniques. The simplicity the ease of manufacturing of the actuators described in this report demonstrate a clear advantages to use of such a system in creating simple robots in applications that may not require complex control systems and require low costs such as disposable robots. The advantages afforded by the soft legs also show promising prospects with regards to fields such as historical landmark mapping or mine fields where the system's low weight and soft legs minimises damage to the environment. Other applications such as collaborative robotics would also benefit from the use of such a system due to the low risks and light-weight design that can be easily mass produced.

While there are techniques that could be applied such as combining the eversion of the tip of each leg to maintain pressure control independently from the length, or using the inflatable chamber design in conjunction with traditional rigid robotics to provide a compliant interactive layer with a rigid and high resolution electronic motor, the system in its current configuration provides a functional robot platform that has been tested over flat terrain without the added complexity, and while these techniques could be investigated further, they exceed the scope of this report.

From this design, we can either approach a solution that relies less on control systems by emphasising the passive properties, or incorporating techniques such as visual servoing to simulate the motion of the leg to achieve more accurate and predictable responses while maintaining the soft properties.

I think the ideal next step for this projects development would be to optimise the design of the actuators, leg and base, and implement CAM techniques to produce actuators and legs that have a more consistent manufacturing tolerance which could produce better results by allowing the compliant properties to be used for the obstacle avoidance rather than making up for errors in production. A more manufacturing suitable design should also be produced to allow for easier construction and maintenance of the robot for future developments in areas such as control and simulation.

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[4] Manuel F. Silva and J. A.Tenreiro MacHado. A historical perspective of legged robots. *JVC/Journal of Vibration and Control*, 13(9-10):1447–1486, 2007.

[5] Otherlab! Ant Roach inflatable walking robot.

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I'd like to give a special thanks to the people who helped pass the 24/7 library open times for their contributions to my ability to study as someone who is nocturne. I would also like to thank the cleaners and library staff who kept the library a place that encourages me to learn and work at my best performance.

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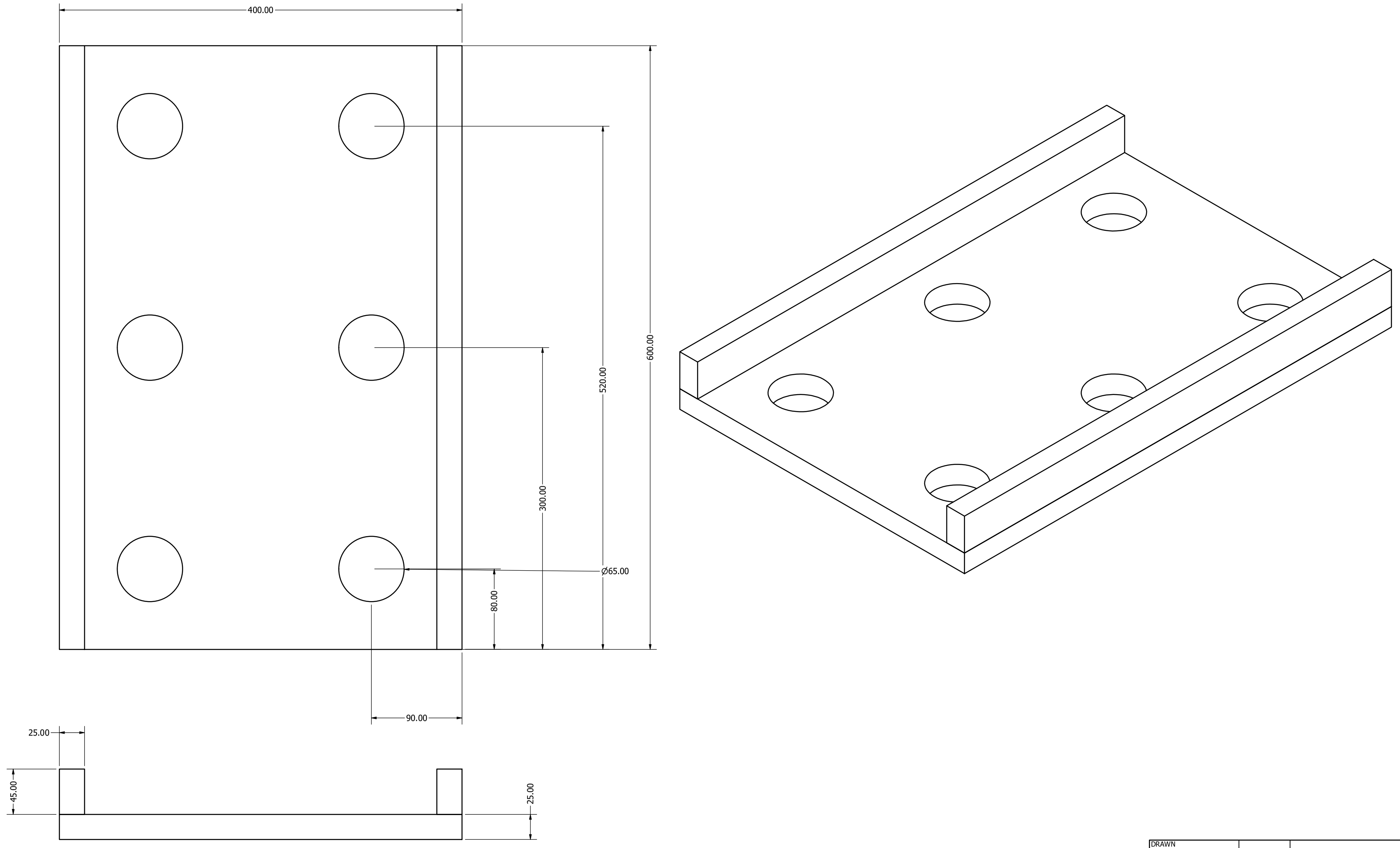
Appendix



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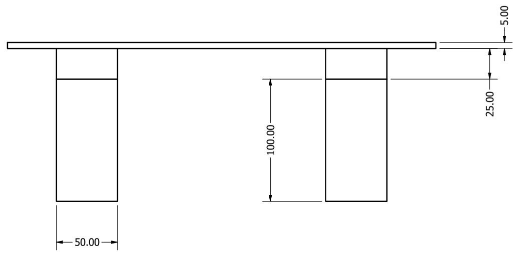

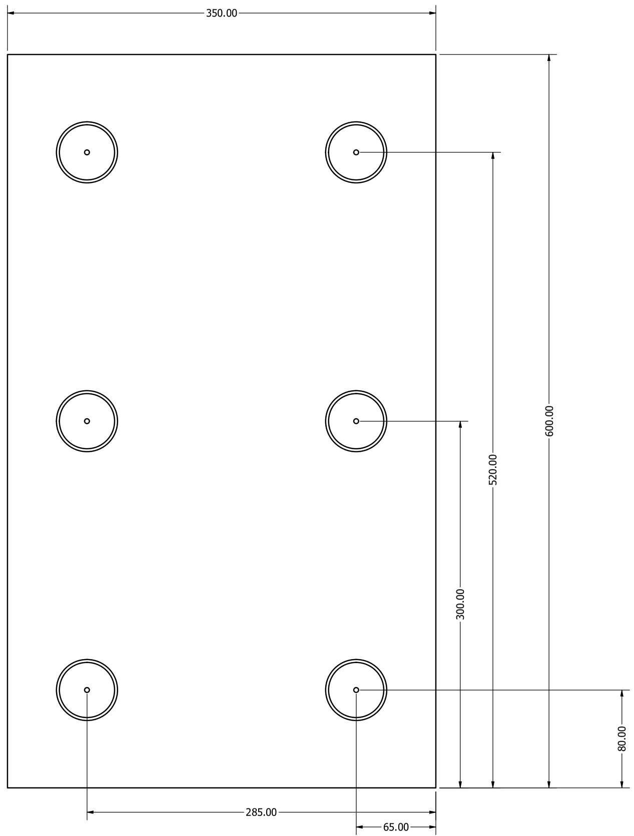

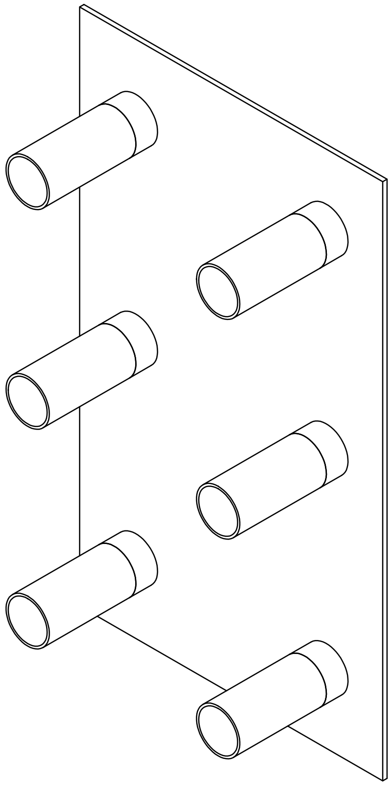

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