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► To cite this version:

Danyaal Kaleel, Benoit Clement, Kaspar Althoefer. A Framework to Design and Build a Height Controllable Eversion Robot. The 11th International Conference on Control, Mechatronics and Automation, IEEE, Nov 2023, Grimstad, Norway. pp.239-244, 10.1109/ICCMA59762.2023.10374973 . hal-04322508

HAL Id: hal-04322508

<https://ensta-bretagne.hal.science/hal-04322508v1>

Submitted on 5 Dec 2023

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A Framework to Design and Build a Height Controllable Eversion Robot

Danyaal Kaleel

*School of Engineering and Materials Science
Queen Mary University of London
London, United Kingdom
d.m.kaleel@qmul.ac.uk*

Benoit Clement

*CNRS IRL Crossing
Ensta Bretagne
Adelaide, Australia
benoit.clement@ensta-bretagne.fr*

Kaspar Althoefer

*School of Engineering and Materials Science
Queen Mary University of London
London, United Kingdom
k.althoefer@qmul.ac.uk*

Abstract—Eversion robots are used in many different environments for a variety of applications. However, the vast majority of these environments are land based and minimal work has been done on environments that are 3-dimensional (3D) such as in air or underwater. To be able to successfully operate in such environments, eversion robots need to be capable of operating in 3D, including adjusting their configuration along the vertical axis. This vertical motion for eversion robots has not been developed before. This paper proposes a design for an eversion robot that, when fully extended, is able to float in air, using varying amounts of helium to change its buoyancy and hence, the amount of lift force in the vertical direction. The robot in this paper consists of a fixed base, one main continuous everting chamber with a constriction at half its length to form two links and two actuation pouches, which are externally attached. Furthermore, the calculations for determining the quantity of helium required to generate a specific force to lift the robot a specified distance, for position changes is shown. Finally, a kinematic model of the robot shows how the robots link tip positions affect the shape and position of the robot.

Index Terms—soft robot design, eversion robot, vine robot

I. INTRODUCTION

Robots constructed from soft materials can be applied to environments and be used in applications that traditional rigid robots cannot. This is due to their advantageous material properties of being flexible and deformable, which enable these robots to be adaptable to changes in their environment. An eversion robot is a soft robot, in the shape of a cylindrical tube, that extends in length from its tip by shifting pressurised body material through its inner body and pushing it out at its tip [1]. Eversion robots are able to extend in length from their tips using either pneumatic pressure, like those seen in [2] or hydraulic pressure, like those seen in [3]. Eversion robots can extend themselves to reach a target [4], they can retract themselves [5], and they can steer themselves [6], over a horizontal plane with very little to no vertical movement, by bending their bodies in different directions [7]. Typically, the environments in which these robots are seen to operate in are land-based environments, such as those seen in [8], where the robot is on the ground and is only able to move on a 2-dimensional plane (2D).

This work was supported by the UK-France joint PhD programme jointly managed by the Defence Science and Technology Laboratory (DSTL) and the French MOD's Defence Innovation Agency (AID).

Eversion robot motion are fairly well documented in the literature for eversion robots that operate in 2D land-based environments. One of the few pieces of literature that investigates an eversion robot in a 3-dimensional (3D) environment is a paper that describes the development of an eversion robot for the exploration of a coral reef [9]. This paper developed an eversion robot system that was capable of extending itself and retracting itself underwater [9]. It used the surrounding water to enable extension and also provide neutral buoyancy [9]. However, neither buoyancy control in the vertical direction nor horizontal steering was possible with this system. It instead relied on contact with its environment to change the direction at which it bends [9]. Not relying on environmental contact and being able to choose the direction that the robot moves in is important for robotic applications. An essential movement to bring eversion robots into 3D environments, such as an underwater environment, is the robots ability to move in the vertical direction. In particular, its ability to change and remain at a specific depth underwater or height or altitude in air.

Therefore, this paper aims to 1) provide a possible design for an eversion robot that is capable of changing its depth through varying the internal concentrations of a lighter fluid (in this case helium) compared to the fluid that makes up its environment (in this case air), 2) provide calculations that enable researchers to determine the quantity of helium needed for a specific displacement in the vertical direction, 3) calculations that determine the force exerted with a specific quantity of helium, which are essential to the successful deployment of this type of eversion robot in environments that are fragile and delicate, and 4) a kinematic model to determine the shape and position of the eversion robot for a given link tip position, and providing researchers with a kinematic model to use as a comparison for the actual physical system. It is hoped that the work in this paper can further the development of eversion robots operating in 3D environments, especially underwater environments as we believe eversion robots will be beneficial for a number of underwater activities due to their inherent advantageous properties. These advantageous properties of using eversion robots underwater include creating very little disturbances or damage to the environment, due to having a friction-less extension movement with their environment [10], being compact and short for storage and travel, which could be

useful if being deployed on a small ship and then growing into a large and long size [11], which would be useful as bodies of water, such as the ocean, are vast and deep, and having a soft structure which enables them to morph their shape to suit their environment [12], which would be useful for moving through narrow passageways and crevices. These advantageous properties would enable eversion robots to be applied to many underwater applications including underwater search and rescue, underwater archaeology, underwater exploration of marine environments and underwater mine fields clearance [13]. Although the purpose of this paper is to establish a first step for developing eversion robot depth or buoyancy control in an underwater environment, a floating eversion robot in air is a completely novel concept that has not been done before and so this paper provides a pivot on which researchers can be pointed in a useful direction to develop robots in this area also.

This paper is structured as follows: Section 2 proposes an eversion robot design, that would be capable of altering its vertical position, including the materials, dimensions and components. Section 3 presents the calculations for the quantity of helium required to generate the force needed to cause a specific vertical position change of the robot's link tips and the calculations for the force generated by this quantity of helium. Section 4 discusses a kinematic model that models the robots position for a given vertical displacement. Section 5 presents the conclusions and what future researchers can do to improve upon this work.

II. ROBOT DESIGN

The robot in this paper had two distinct main sections: a static rigid base and a soft flexible everting membrane with two buoyancy actuation pouches, as shown in Fig. 1. The everting body of the robot was connected to the base using the base's pneumatic fitting that supplies air to the everting body by screwing the excess plastic sheet material that makes up the everting body to this pneumatic fitting. Note that the eversion robot body is to be filled with air and the two actuation pouches are to be filled with varying amounts of helium to cause the robots shape and link positions to change.

A. Robot Base

The rigid fixed base, shown in Fig. 2, was made from an airtight plastic box, which has holes in for the pneumatic fittings. Rubber o-rings were placed on the female and male parts of the pneumatic fittings before they were connected to the base to prevent leaks. The pneumatic fittings were used for connecting an air supply to the everting section of the robot and a helium supply to the buoyancy actuation pouches. This was achieved using internal pneumatic tubes within the base of the robot to connect the air inlet with the air outlet and helium inlets with the helium outlets. To achieve the position shown in Fig. 1, the exploded view diagram of the base, shown in Fig. 2, is rotated by 90 degrees around the vertical axis.

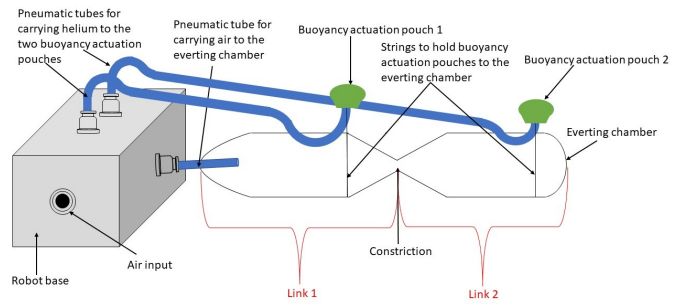


Fig. 1. Eversion Robot Design

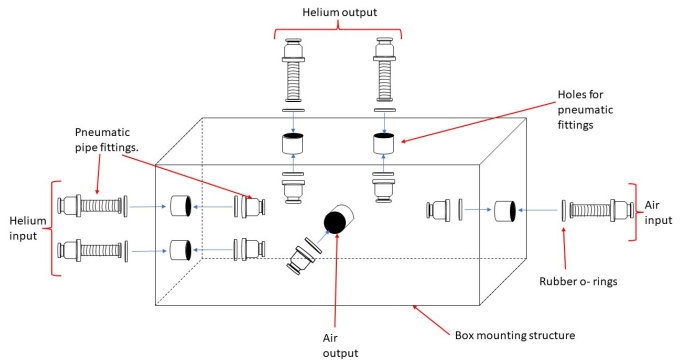


Fig. 2. Fixed Eversion Robot Base

B. Eversion Robot Body

According to the tests conducted by [14], helium has a lifting capability of 0.95 kg/cubic metre at room temperature. The materials that are used to construct the eversion robot were therefore chosen to be light to enable the helium to have an effect on the flotation height. The eversion robot body was made from thin plastic sheets that were heat welded together and the pneumatic pipes and altitude control pouches were made from rubber. The dimensions of the everting body of the robot are shown in Fig. 3. The two links of the robot were created by making a constriction in the robot using heat welding. This created a hinge between the links enabling bending while also allowing the robot to extend. The mass of links 1 and 2 were measured to be 0.084 kg and 0.038 kg. The mass of link 1 included the masses of the pneumatic tubes, the weight of the eversion robot body itself and the mass of the actuation pouch at tip of link 1 as these structures had their centres of mass concentrated on link 1. The mass of link 2 only included the mass of the actuation pouch at the tip of link 2.

III. CALCULATIONS FOR LIFT

To determine the quantity of helium required to generate the required force to lift the robot, we first have to consider the robot's initial position and the forces that influence the robot's

position. The weight and lift forces of the links are shown in Fig. 3 and the initial position of the robot is shown in Fig. 4.

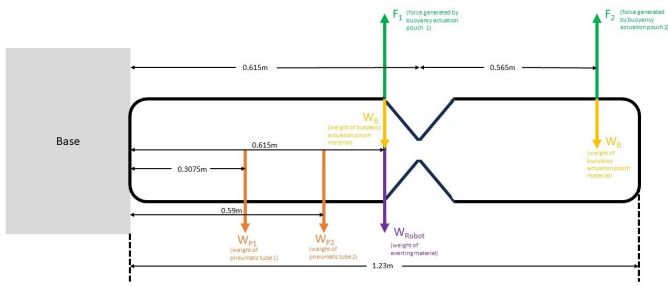


Fig. 3. Forces that influence the robot and where these forces act based on the distance of the centre of mass, from the base, for distributed forces and based on the distance, from the base, for point forces.

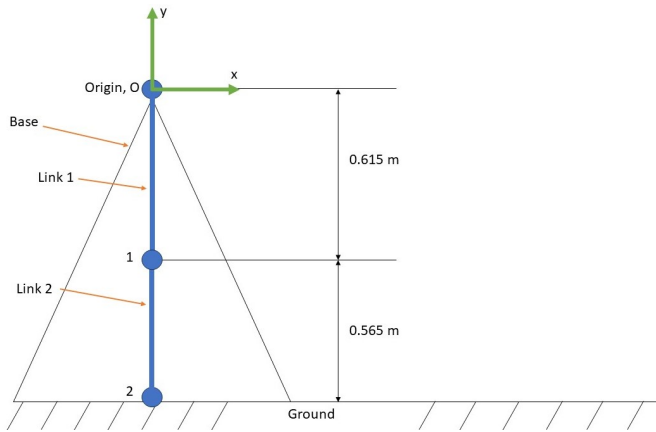


Fig. 4. Robot's initial position in resting position.

A. Modelling Assumptions

The first modelling assumption that has been made was that the weight and lift force that is concentrated over link 1 has no influence on the lift force generated at the tip of link 2 and the weight and lift force concentrated over link 2 has no influence on the lift force generated at the tip of link 1. The second modelling assumption is that the robots' length is the same as the distance from the ground to the origin of the robot, shown in Fig. 4. This helps in the following calculations to determine distance travelled to reach equilibrium. However, if the robot length was not the same as the distance of the origin of the robot to the ground, in that the robot was at a higher distance off the ground, then the distance at which equilibrium is achieved is vertically offset by a distance d , which is the distance to the tip of the second link at initial position. The final modelling assumption is that the eversion robot is assumed to be fully everted or extended when the helium is to be injected into the buoyancy actuation pouches.

B. Determining Quantity of Helium for Equilibrium

To achieve equilibrium of each link, shown in Fig. 5 and 6, which is where the lifting force is equal to the weight of the

robot causing the robot to float in the air without moving up or down, a certain quantity of helium is needed to generate this lifting force. To determine the quantity of helium required to lift links 1 and 2 to equilibrium, (1) can be used along with the known mass of link 1 and link 2 of the robot and the lifting capability of helium (LCH) from [14], which is 0.95 kg/m^3 .

$$Q = m/LCH \quad (1)$$

where Q is the quantity of helium in m^3 , m is the mass across the link in kg and LCH is the lift capability of helium, which is 0.95 kg/m^3 , according to [14].

Using the modelling assumptions above and the mass, m , across link 1 and 2, as 0.084 kg and 0.038 kg respectively, we can calculate Q for link 1 and 2 as $Q_1 = 0.09 \text{ m}^3$ and $Q_2 = 0.04 \text{ m}^3$.

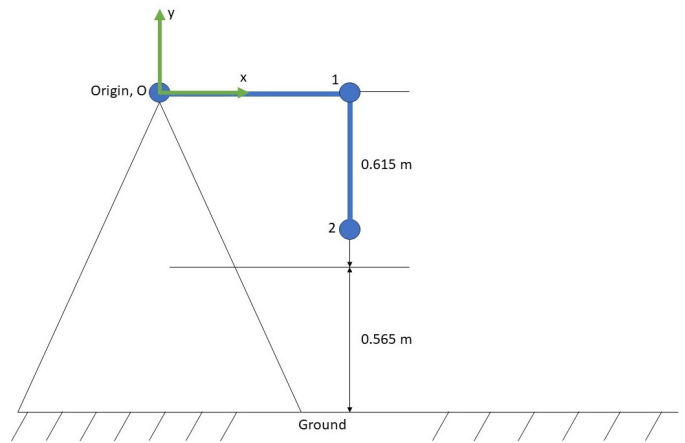


Fig. 5. Robot's equilibrium position of first link with respect to the ground.

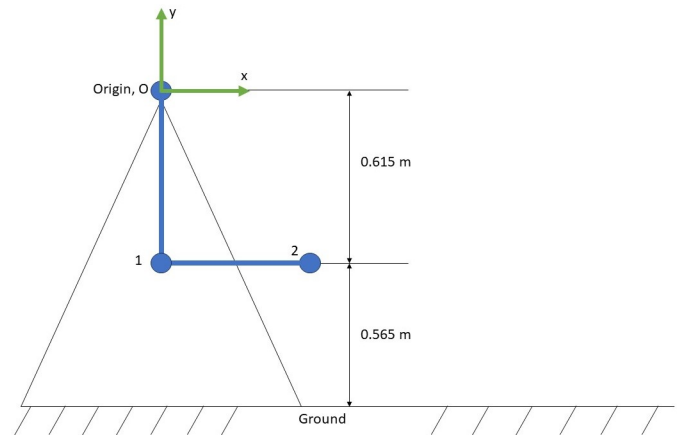


Fig. 6. Robot's equilibrium position of second link with respect to the ground.

C. Determining Force Generated by Quantity of Helium at Equilibrium

To calculate the force produced by the quantity of helium at equilibrium, we know that at equilibrium the forces are balanced. In other words, the weight forces pulling the robot

down equal the lift forces holding the robot up. With this information, we can calculate the force produced by the quantity of helium at equilibrium using (2):

$$F = m \times g \quad (2)$$

where F is the force produced by the amount of helium, m is the mass of the link in kg and g is the gravitational acceleration, which we have taken as an approximate value of 9.81 m/s^2 [15]. For the robot design in this paper, we get a force for link 1, F_1 of 0.82404 N and a force for link 2, F_2 of 0.37278 N .

D. Determining the Quantity of Helium for a Specific Vertical Displacement

Since we know the quantity of helium that will produce the required force to achieve a known displacement, based on the definition of the robots position relative to the ground, shown in Fig. 4, 5 and 6, we can calculate the quantity of helium to get a displacement of n in the vertical direction. The equation for this calculation is shown using (3) below.

$$Q_n = n/d \times Q \quad (3)$$

where n is the displacement in the vertical direction in m , Q_n is the quantity of helium required to achieve n displacement in m^3 , d is the distance to equilibrium in m and Q is the quantity of helium to achieve equilibrium in m^3 . For example, if you wanted a displacement of n metres for link 1, you could use (4).

$$Q_n = n/0.615 \times 0.09 \quad (4)$$

If n is 0.1 m , then this tells you that the required quantity of helium to lift the robot by 0.1 m is 0.01 m^3 .

E. Determining the Force Produced by a Specific Quantity of Helium

Many applications involving eversion robots require the eversion robot to exert little force on the environment. Knowing the force output that the robot generates is useful to know as force can be controlled for. An application where force control is important, is search and rescue applications for earthquakes, such as those seen in [16] and [17], where care must be taken to prevent debris from falling on top of someone. Another application where force control is important is pick and place, as seen in [18], where forces involved in moving objects must be considered. Equation (5) gives us a way to calculate the force exerted by the robot using the quantity of helium.

$$F_n = Q_n \times g \times LCH \quad (5)$$

where n is the displacement in the vertical direction in m , F_n is the force exerted by the robot to achieve n displacement in N , Q_n is the quantity of helium to achieve n displacement in m^3 , g is the gravitational acceleration on the Earth surface, which we have taken as an approximate value of 9.81 m/s^2 [15] and LCH is the lift capability of helium, which is 0.95 kg/m^3 , according to [14].

IV. KINEMATIC MODEL FOR ROBOT POSITION

To verify the lift calculations above, a kinematic model, shown in Fig. 7, was developed.

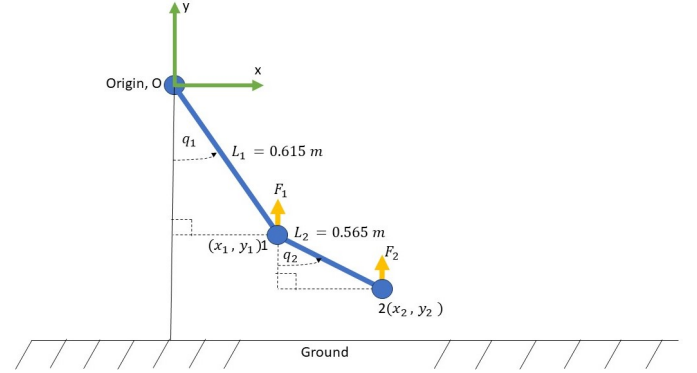


Fig. 7. Kinematic chain diagram of robot

A. Inverse Kinematics to Determine Required Bending Angles

Considering Fig. 7, we can calculate the desired angles of the links, q_1 and q_2 , using the desired position of the links in the y -direction and (6) and (7).

$$q_1 = \arccos(y_1 / -L_1) \quad (6)$$

$$q_2 = \arccos(y_2 / -L_2) \quad (7)$$

where q_1 and q_2 are the desired angles of the links with respect to their initial position shown in Fig. 4, y_1 and y_2 are the desired position of the link tips in the vertical (y) direction and L_1 and L_2 are the lengths of the links.

B. Determining the Shape of the Robot

After obtaining the required angles, q_1 and q_2 , for a particular desired position, y_1 and y_2 , we can determine the shape of the robot using the forward kinematic equations shown in (8), (9), (10) and (11).

$$x_1 = L_1 \times \sin(q_1) \quad (8)$$

$$y_1 = -L_1 \times \cos(q_1) \quad (9)$$

$$x_2 = L_1 \times \sin(q_1) + L_2 \times \sin(q_2) \quad (10)$$

$$y_2 = -L_1 \times \cos(q_1) - L_2 \times \cos(q_2) \quad (11)$$

where x_1 , y_1 , x_2 and y_2 are the x and y coordinate positions of the tips of links 1 and 2 with respect to a positive x and y axis shown in Fig. 7, L_1 and L_2 are the link lengths and q_1 and q_2 , are the angles of the links for a particular desired position.

C. Verification of Kinematic Model

The kinematic model was implemented in MATLAB [19] to determine whether the shape of the robot was what was expected for the initial position of the robot, the equilibrium positions of links 1 and 2, and for equilibrium of both of the robots links. Comparing Fig. 8, which is the MATLAB plot of the initial position, to the expected initial position of the robot, shown in Fig. 4, shows that the kinematic model's calculated initial position of the robot is correct. Further, comparing the MATLAB plots produced, in Fig. 9, that shows the robot achieving equilibrium with the expected equilibrium positions, shown in Fig. 5 and 6, further validates this kinematic solution. Fig. 10 shows that solutions are also produced for random values of y_1 and y_2 between the values of $-0.615 \leq y_1 \leq 0.615$ and $-0.565 \text{ m} \leq y_2 \leq 0.565 \text{ m}$. These random values of y_1 and y_2 show that the model is not inclusive to only certain y_1 and y_2 values, such as those achieved at equilibrium and the initial position of the robot and that other positions of y_1 and y_2 can be achieved. Note that the 0.615 m and 0.565 m are the maximum lengths of the links and we are assuming that the robot is fully extended, when the actuation control pouches are being inflated with helium for height change. The vertical position coordinate values of y_1 and y_2 for determining the kinematic positions of the links shown in Fig. 8, 9 and 10 are shown in Tab. I.

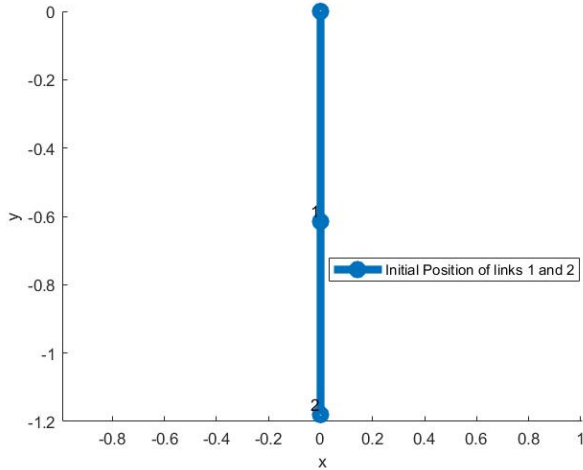


Fig. 8. Initial position of robot determined using the kinematic model.

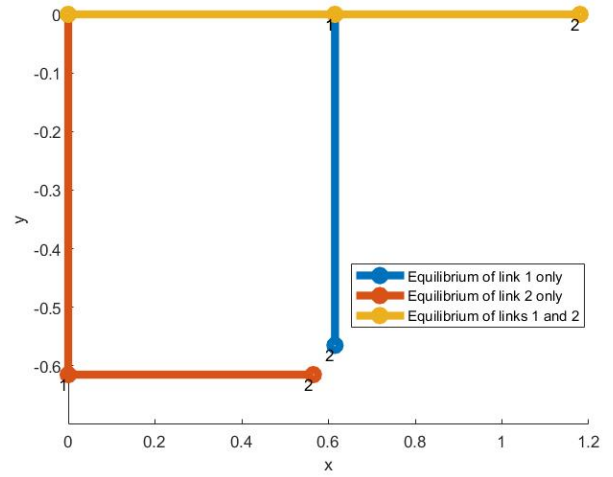


Fig. 9. Equilibrium position of robot determined using the kinematic model.

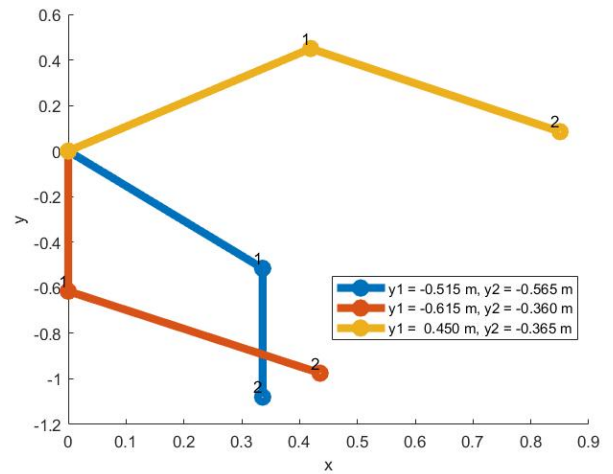


Fig. 10. Random positions of robot can be reached including positive, which have been determined using the kinematic model.

This affirmation of the kinematic model shows that it would make a good comparison for work involving a physical height controllable eversion robotic system.

V. CONCLUSIONS AND FUTURE WORK

The aim of this paper is to pave the way for motion control developments of eversion robots in 3D environments, which has not been done before. The paper started by proposing a potential design for a two-link eversion robot that is capable of altering the vertical height of its links using helium in externally mounted actuation pouches. A stand out feature of its design is the light weight materials used in its construction to enable helium to produce enough lifting force. Secondly, this paper showed the required calculations to determine the quantity of helium and the force that is generated from that quantity of helium that will result in a specified change to the vertical position of robots links. Lastly, this paper showed a

TABLE I

VALUES OF y_1 AND y_2 FOR DETERMINING THE KINEMATIC POSITIONS OF THE LINKS SHOWN IN FIG. 8, 9 AND 10

Figure	y_1	y_2	Shows	Colour
8	-0.615	-0.565	Initial Position	blue
9	0	-0.565	Equilibrium of link 1 only	blue
9	-0.615	0	Equilibrium of link 2 only	orange
9	0	0	Equilibrium of links 1 and 2	yellow
10	-0.515	-0.565	Random Link positions	blue
10	-0.615	-0.360	Random Link positions	orange
10	0.450	-0.365	Random Link positions	yellow

kinematic model to determine the shape of the robot when given a vertical coordinate position for each of the two links. The work described in this paper is a first step towards developing an eversion robot that can alter its height using a lighter fluid in externally mounted actuation pouches.

Further work should look into testing a physical eversion robot prototype with the calculated quantities of helium for specific distances to see if they can be reached and compare it to the kinematic model in this paper, which is the ideal case. Additionally, an improved model for determining the quantity of helium is needed, that takes into account how the weight of link 1 and the lift force at the tip of link 1 affects the lift force needed to be generated at the tip of link 2 and vice versa. Lastly, a suitable controller needs to be developed to control eversion robots in 3D environments that can accommodate for all the different movements that eversion robots are capable of but also one that takes into account the complexity of the environment that the robot is moving through. A controller that uses reinforcement learning and artificial intelligence (AI) could be an ideal approach to investigate due to the highly nonlinear motion behaviour of eversion robots. Given that eversion robots are a type of continuum robot, continuum robot control systems should be investigated, such as [20]. Furthermore, a suitable model of the robot moving through its environment could be used for developing control strategies. One could look to underwater vehicle modelling such as [21], for inspiration.

ACKNOWLEDGMENT

A special thank you to our collaborator Dr Adrian Baker from DSTL for his help on this project.

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