Mechanically Programmable, Degradable & Ingestible Soft Actuators

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Abstract— **One of the key challenges in soft robotics is the development of actuators which are truly soft and compliant, and can be adapted and tailored for different applications. In particular, the development of untethered soft actuators could enable robots to autonomously explore the world in an unrestricted manner, exploiting their compliant behavior. In this paper we present a method for creating fully soft, degradable actuators where the actuation of the system is controlled by setting physical parameters which 'mechanically program' the actuator determining the characteristics of the actuator. The actuation process is driven by the release of gas from a reaction between a bio-compatible acid and base. This approach allows for the creation of fully untethered actuators which could be deployed for use in agriculture, to make ingestible robots or to allow untethered exploration. This paper provides the 'recipes' for the development of the actuators used, and the methods for mechanically programming of the actuators.**

I. INTRODUCTION

The compliant nature of soft robots provides the potential to explore or reach places that a more rigid equivalent can not [1]. This could include exploration within the human body or burrowing in sandy terrain within a muddy field. However, soft robots are often limited by actuation technologies with many soft actuators requiring large energy sources or compressors, or needing bulky on-board controllers which constrain their size compliance [2], [3]. These physical limitations of the actuators can limit the applications for which they can be used. The development of untethered, entirely soft actuators which do not require additional controllers or tethers could enable application in areas such as agritech or challenging exploration [4]–[6].

A. Goals & Use Case

The goal of this work is to develop an entirely soft and untethered soft actuator where the system can be programmed mechanically to avoid the need for any additional onboard controller. The system must also incorporate its own on-board energy source and have material properties which enables degradation, to allow the actuator to deployed without requiring retrieval. Finally, the materials must be biocompatible, non-volative and food safe to allow deployment in many situations including within or around biological systems.

There are two specific use cases that we will consider for this new actuation technology:

- **Ingestible small scale robots** for deployment of drugs or exploration of the body. This would extend previous work on origami pill robots ([7]) to allow systems which could be self-propelled through the body.
- **Deployable agricultural robots** for autonomous exploration in field environments. Imagine dropping a batch of disposable cellular robots on a field; they could crawl to find plants and embed themselves in the soil, delivering nutrients and dissolving upon completion.

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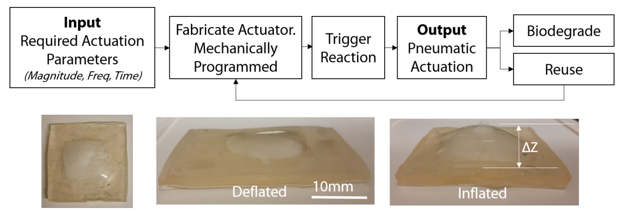

Fig. 1: Top) Summary of the life=cycle for the mechanically programmable biodegradable untethered actuator from design to application. Bottom) Demonstration of the actuation technology showing the actuator at both the deflated and inflated points of the actuation cycle.

B. Previous State of the Art

There has been a significant number of approaches for developing untethered soft robots [8], [9]. This has included a entirely soft 3D printed octopus system powered using chemical reactions micro-fluidic controllers [10], jumping robots powered by combustion [11], ingestible robots [7] and also soft untethered grippers [4]. In addition developing new actuators, to achieve entirely soft actuators it is also necessary to develop new approaches for control which do not require rigid or bulky on-board controllers. One approach is the concept of mechanical programming, or morphological computation [12], where the physical properties are exploited for control purposes [13]. Previous actuation techniques have exploited instabilities in soft structures [14], or using soft bistable valves [15] to control actuation. In addition to exploiting the mechanical properties, the material properties can also be controlled to provide or enable certain functionality.

With the increasing focus on more environmentally conscious solutions, there is increasing interest in biodegradable robots [16], or even edible robots [17]. As such, there is a need for a soft biodegradable actuation systems which has favorable and controllable properties.

C. Proposed Approach

We propose an actuator design which uses a degradable gelatin-glycerol mix. This material is used to create pouch based actuators, with a small valve in top surface of the actuator. A chemical reaction is used to internally create gas, which leads to an increase in the internal pressure and growth of the actuator, until the valve opens and the actuator resets to its initial size. This leads to a cyclic actuation pattern. The mechanically properties of the actuator can be used to control the cyclic actuation pattern. By developing the actuators using the gelatin-glycerol material, the actuators show soft, elastic behaviors whilst also being biodegradable and even edible. This approach to actuator design in summarized in Fig. 1.

In this paper we demonstrate this new actuator and show how it is possible to mechanically program the behavior. As such, this paper makes a number of contributions:

- Design rules for the mechanical programability of actuators using the concept of exhaust valves and continuous gas production
- Recipe for the construction of biodegradable actuators
- Demonstration of integration of the actuators for the two possible use cases: a locomoting system and a small ingestible sized actuator

In the following section the methods and design principles are presented. Section III presents the fabrication 'recipes' and design methods for the actuators. Experimental results are given in Section IV, with a Conclusion and Discussion given in Section V.

II. METHODS & DESIGN PRINCIPLES

A. Actuator Mechanism

The proposed actuator is constructed for a material formed from gelatin and glyerol to provides a base elastomer material that has similar material properties to silicone. Unlike silicone, the material can be easily reused by melting and reforming, or, can be left to naturally degrade. A simple pouch actuator is created by casting two material layers, one thicker than the other, and sealing these two layers. In the top layer, a small valve is added by adding a small slit. The actuator is formed with the powdered acid and base mix in the middle. When water is injected into the system, and the powdered mix become aqueous, they react, releasing gas. This gas causes the pressure within the actuator pouch to expanded until a threshold is reached. At this threshold the bistable valve opens, releasing the gas inside and returning the actuator pouch to the uninflated shape. This leads to a cyclic actuation pattern. The mechanical and physical properties of the actuator can be used to program the parameters of this cycling actuation, namely the frequency, maximum force/expansion and total period of actuation. This untethered actuation mechanism is summarized in Fig. 2. Specific details of the fabrication of both the material and the actuator are given in Section III.

B. Actuator Model

To determine the design criteria for an actuator, a simple model describing the actuator has been developed. The parameters of the model are summarized in Table 1 with a graphical representation of these parameters highlighted in Fig. 2.

1) Energy Source: A number of different approaches for incorporating on board energy sources have been considered for soft robots [18]. For this soft actuator we use an acid and base, specifically citric acid and sodium bicarbonate, where the reaction leads to the release of a gas. This reaction uses chemicals that are readily available, and are 'food safe' [19]. Both are common household chemicals that are used in for cleaning or baking. In the presence of water, citric acid ($C_6H_8O_7$) and sodium bicarbonate ($NaHCO_3$, baking soda) react to form sodium citrate ($Na_3C_6H_5O_7$), water, and carbon dioxide (CO_2):

$$C_6H_8O_7 \ + \ 3NaHCO_3 \rightarrow Na_3C_6H_5O_7 + 3H_2O + CO_2 \tag{1}$$

This reaction leads to the release of carbon dioxide gas which is used to increase internal pressure. To achieve a release of R moles of carbon dioxide, a ratio of R moles of $C_6H_8O_7$ and 3R moles of $NaHCO_3$ should be included in the actuator. In addition to the creation of gas, the reaction also leads to sodium citrate. Although this is a non-toxic compound which is widely used as an acidity regulator in food and drinks, the amount created should be limited for ingestible actuators.

The choice of reactants provides a significantly lower energy density in comparison to many possible alternatives, such as hydrogen peroxide and a base. However, this reaction offers bio-compatability, enabling actuators to be use for ingestiable applications.

2) Actuation Control: The rate of the reaction, r, and hence the rate at which the CO_2 is produced is dependent on the temperature, quantity of water and presence of a catalyst. In this model we assume the actuator is at room temperature, the temperature is constant, and there is no catalyst present. The value of r, and hence the rate of carbon dioxide production for a given amount R of the reactants was found experimentally. Although r is not constant, we use the average rate across the middle 75% of the length of the reaction which is approximately constant.

At time t from the point at which the reaction started, there will be Rrt Moles of gas, which corresponds to a volume of $v = Rrtm_v$ where m_v is molar volume of gas (22.4L), the volume that any one mole of gas occupies at standard temperature and pressure. This increase in volume inflates the actuator. After expansion, the elastic actuator material starts to restrict expansion, resulting in the development of internal forces in the surrounding elastic material of the actuator (F_{walls}). These forces balance the the external force applied by the actuator, F_{ext} and the internal forces F_{int}:

$$F_{ext} = F_{int} - F_{walls} \tag{2}$$

When this pressure exerted on the wall exceeds a threshold, F_{valve}, the bistable valve opens and the internal pressure is released and the volume of the actuator returns to initial volume. The maximum force of displacement that can be

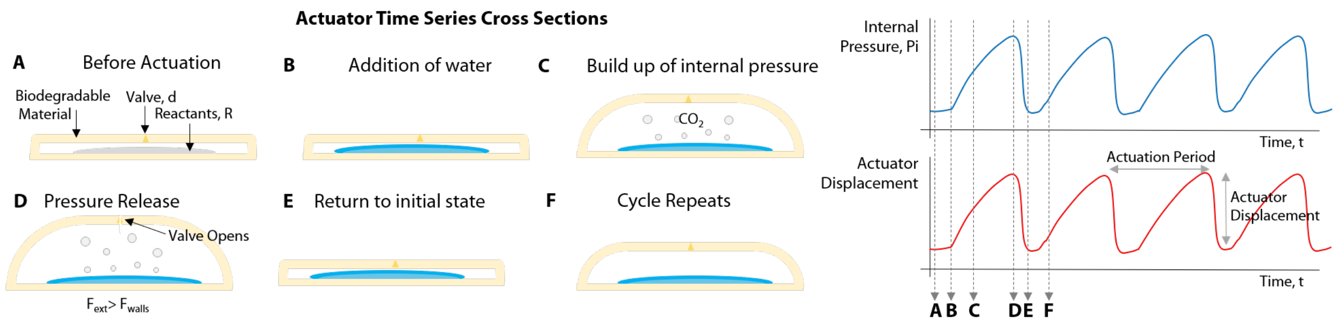

Fig. 2: A-F: Diagrams of a cross-section of the actuator and the design parameters, with the accompanying changes in internal pressure and displacement shown on the right corresponding to the various states shown in A-F.

achieved is determined by the valve properties, namely the size:

$$F_{Max} > F_{valve} \;\; where \;\; F_{Max} \propto v \tag{3}$$

After the valve has opened and the inner pressure has been released, this cyclic operation then restarts, until the reactants have full reacted.

This threshold property of the value is dependent on both the length of the value, d and the material properties. This mechanism relies on the elastic and 'tack' like behaviors of the gelatin actuator material which enables this simple bistable exhaust approach. To empirically determine the value of F_{max} a pressure transducer was connected to the actuator to measure the internal pressure. The pressure was manually increased by pumping air until the valve opens and a drop of pressure is observed by the transducer. In this way, the relationship between valve size and maximum pressure threshold can be determined. Fig. 3 shows the setup used to achieve these measurements and the experimental results. Above a diameter of approximately 2mm the valve gap is too large and does not operate effectively. Smaller diameters allow higher pressures to be achieved.

C. Actuator Design Parameters

Using this model of the actuator we can identify the parameters which determine the behaviors of the actuator: maximum output force (or displacement) ($F_{max}, \Delta Z$), maximum frequency of the actuation cycle (f) and the length of the actuation cycle (L).

The maximum force that can be achieved (assuming that there are sufficient amounts of reactant to create the gas) is determined by the volume of the actuator, and the force that is achieved before the valve opens (F_{max}). Thus the external force, or displacement is determined by:

$$F_{Max} \propto Vd \tag{4}$$

The frequency of actuation is determined by the volume of the actuator (V), the amount of Reactants (R) and the valve size

$$f \propto \frac{dR}{V} \tag{5}$$

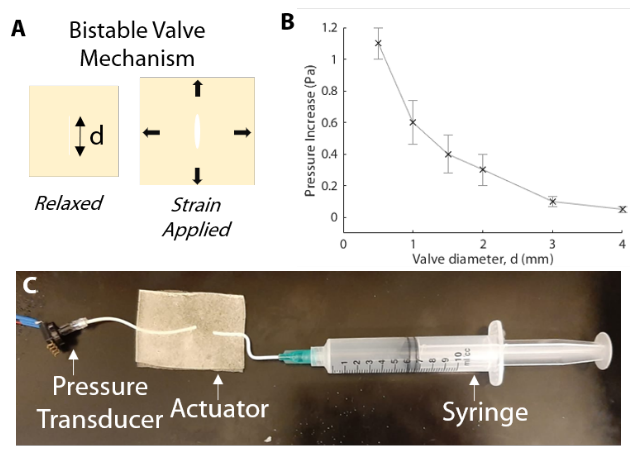

Fig. 3: A) The bistable value mechanism. B) The measured maximum pressure force which was detected when valves of various size, d, where added to the actuators. Each experiment was repeated 5 times with the mean and standard deviation given. C) Experimental setup for gaining these experimental results.

The length of the actuation cycle (T) is dependent on the amount of reactants (R) and the reaction rate (r) and is thus given by:

$$T = R/r \tag{6}$$

As such, there is a limit on the length of operation of the actuator. This is determined by the amount of reactants and corresponding volume of water. It has previous been identified that 165.2 L of carbon dioxide with flow rates up to about 1.7 L/s can be created per kilogram of reactants for this reaction [18].

III. FABRICATION RECIPES

In this section, detailed recipes for the design and creation of the degradable elastomer material and the corresponding actuators are given.

A. Degradable Gelatin Elastomer Material

To create the biodegradable elastomer gelatin, glycerol and water are combined with a mass ratio of 1:6:5 respectively.

TABLE I: Summary of the controllable input parameters of the actuator, descriptive parameters, and also the measurable output parameters.

	Parameter	Symbol	Description
Inputs	Amount of Reactant	**R [Moles]**	
	Valve Size	**d [mm]**	Length of valve
	Actuator Volume	**V**	
Params.	Rate of reaction	**r** $[molL^{-1}s^{-1}]$	Rate of reaction
	Volume of gas	**V**	
	Internal Pressure	P_i **[Pa]**	
	Valve Force Limit	F_{valve} **[N]**	
Outputs	Actuation freq.	**f [Hz]**	Average rate of actuation
	Max Force	F_m **[N]**	Max Force of the actuator
	Max Displacement	ΔZ **[m]**	Max displacement
	Length of Actuation	**T [s]**	Length of Actuation

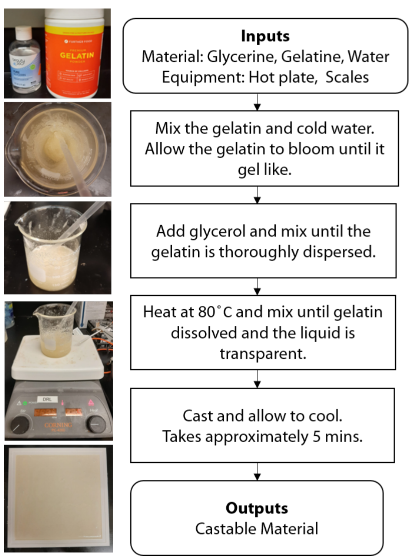

Fig. 4: Process for fabricating the gelatin glycerol mix which can then be casted into a required shape or form.

Firstly, gelatin (bovine, flavour free, food grade) is mixed with the cold water. It is then left briefly (30 seconds) to allow the gelatin to bloom. The gelatin in then added to the mix, and a hot plate (at approximately 80^0C, to prevent boiling) used to heat the mix to allow the gelatin to dissolve. This process is summarized in Fig. 4. Gelatin has been previously investigated as a means of developed biodegradable or even self-healing robots [20].

The material properties of the base material were investigated by cyclic extension testing and tensile testing. The results are given in Fig. 5. For reference, the material properties of an non-biodegradable equivalent, EcoFlex 00-30 (Smooth On), has been presented.

These results show that the gelatin based material shows a greater hysteresis that silicone and is approximately twice as stiff. The tensile limit of the material is also significantly lower, with the material fracturing at strains approximately 40% lower than the silicone. However, the response of the material appears to be most elastic upto this limit, showing a reasonable range of elastic behavior before plastic defor-

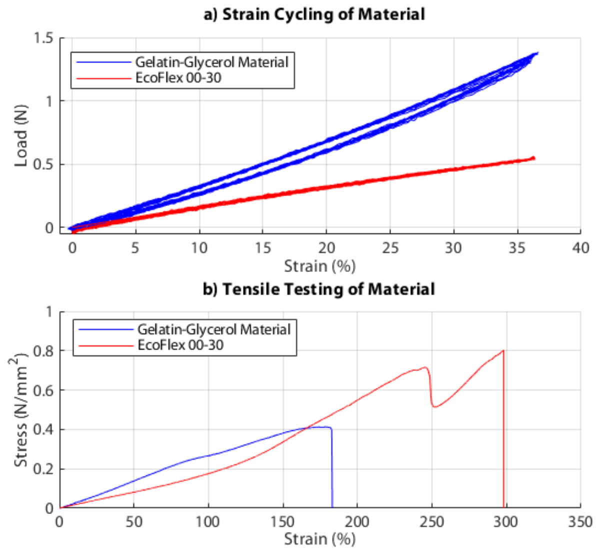

Fig. 5: Material testing of the biodegradable material. Dog Bone samples of width 5mm, length 100mm and depth 2.5mm were tested. A) Cyclic strain testing to investigate hysteresis, B) Tensile testing of the material. Tests were performed using an Instron Machine.

mation is observed. The gelatin mix material has a poorer performance than the silicone. However, the material can be rapidly reformed and reused, shows bio-compatability and shows degradable behaviors, providing alternative opportunities to standard elastomers used in soft robotics. The base materials are also easy to purchase and cheap.

1) Food Safety: The raw materials used to develop this material are both considered to be food safe and are used widely in food and drugs. Gelatin is widely used as a setting agent for food products and is an animal product [21]. Glycerol is a colorless, odorless and viscous liquid that is sweet-tasting and non-toxic; it is has been show to have antimicrobial and antiviral properties. It is widely used in pharmaceutical, or, as a food sweetener or texture enhancer [22]. Thus, these properties make the actuator food safe, allowing it to be safely ingested.

B. Actuator Design

Using the experimental characterization, an approach for developing mechanically programmable actuators has been created. The recipe which specifies the steps and 'ingredients' required to fabricate the actuators is given in Fig. 6. It takes approximately 20 minutes to fabricate a set of actuators, with most of this time due to the mixing and setting times of the material, once the material have been formed (as in Fig.4) the actuator takes approximately 5 minutes to fabricate. The raw material cost for the actuators is approximately \$0.50

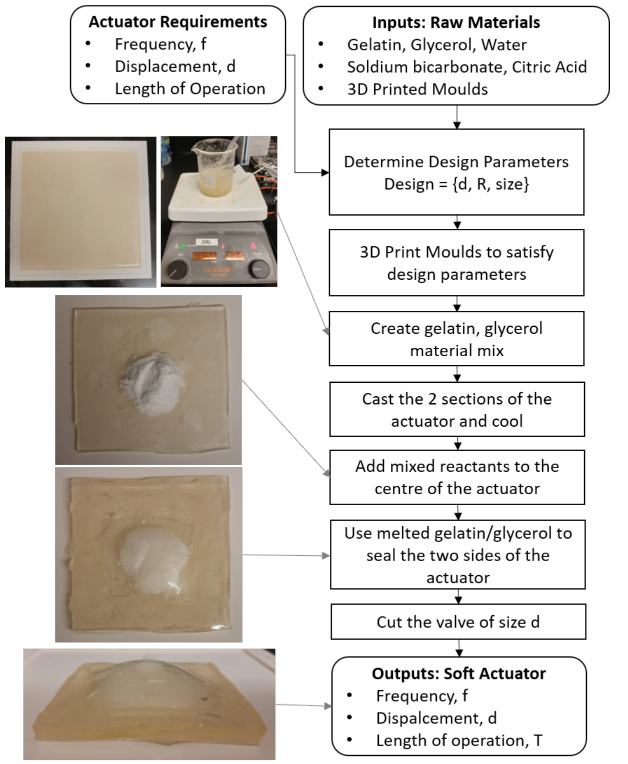

Fig. 6: Recipe for the creation of the mechanically programmable actuators.

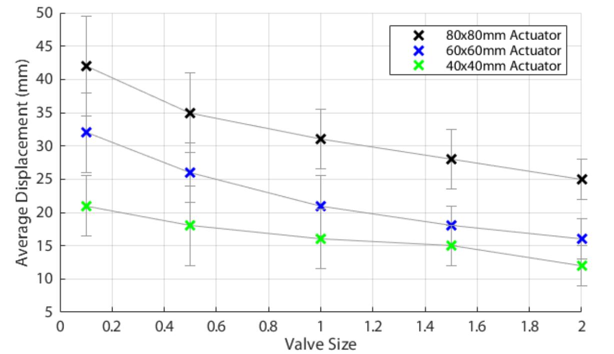

Fig. 7: Average actuator displacement over the entire period of motion for actuators of different volumes and valve size.

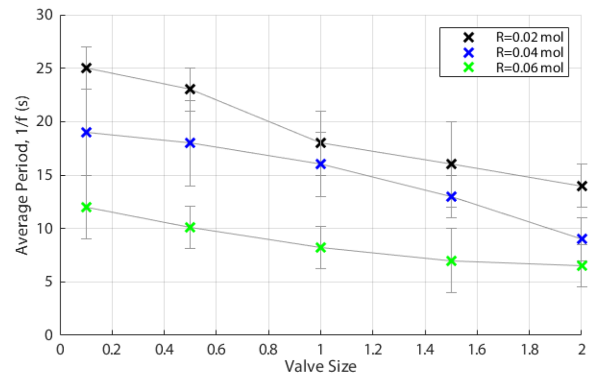

Fig. 8: Frequency of actuation of actuators constructed with different amounts of reactants and for different valve sizes. All experiments were undertaken on a 60mm x 60mm actuator.

IV. RESULTS

A. Actuator Programmability

In this section we demonstrate the ability to alter the behaviors of the actuators by varying the design parameters. In particular we demonstrate the ability to control the force and displacement, the frequency of the actuator and the length of the actuation.

1) Actuator Force/Displacement: The design rules in Section III indicate that maximum force or displacement is determined by the actuator volume and valve size. Therefore, actuators of different sizes, and hence different volumes, and with different valve sizes were investigated. The average displacement per actuation cycle was found over the length of actuation of each actuator. The experimental results (Fig. 7) show that the displacement can be programmed by increasing the volume, leading to larger displacement, and also increasing the displacement by reducing the valve size. This reinforces the design rules identified earlier. It can be seen there is variation in the average displacement, in particular for larger volume systems. Although a wide range of different displacements can be achieved, the maximum displacement is limited by the size of the actuator.

2) Frequency of Actuation: The frequency of actuation (f) is dependent on the time taken to overcome the pressure limit of the valve. Assuming the rate of reaction is constant, the frequency varies with the size of the actuator, valve size and amount of reactants. Here we measure the period of actuation cycle for different valve sizes and amount of reactants (Fig.8). The period $(1/f)$ was found by measuring the time between observed peak displacement and finding the average value for the entire actuation sequence. As the frequency is dependent on the rate of reaction, which reduces as reactants are consumed, we consider the average period for the middle 50% of the actuation process.

3) Length of Actuation Period: To demonstrate the ability to change the length of the actuation period, the amount reactant in actuators of two different sizes (80mm x 80mm) and (60mm x 60mm) with a fixed valve size ($d = 1mm$) were investigated. For the different amounts of reactant, the time during which there was observable actuation was measured. The estimated time from the model was compared to the experimental results.

Fig. 9 shows how the molar quantities of the acid (where the 1:3 ratio between acid and base as determined by (1) is used) change the length of the actuation period.

In both cases the model predicts shorter times than those reported, mostly likely as the rate of reaction is lower than expected. The length of actuation period, T, should be independent of the size of the actuator, however the results indicate that the smaller actuator results in short lengths of operation, which is closer to than of the model. It is suspected

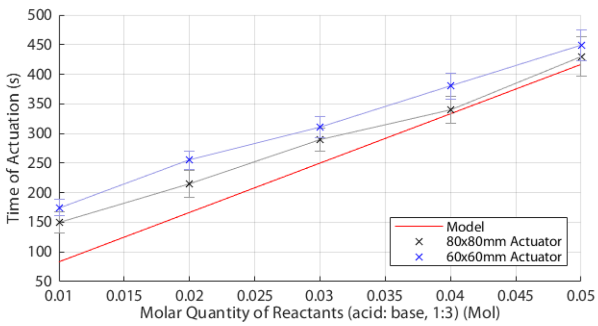

Fig. 9: Model and extended length of time for which the actuator is active. Investigated for actuators of two different times, with each experiment repeated 4 times.

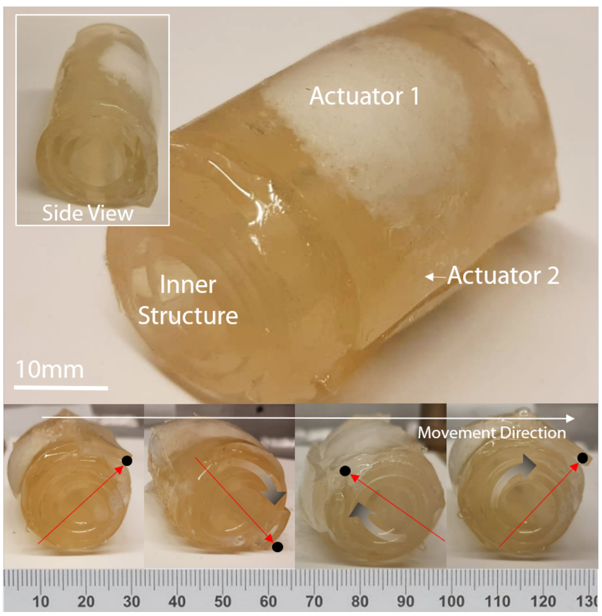

Fig. 10: Rolling system with two actuators incorporated which allows the rolling motion to be triggered.

that the smaller volume leads to better contact and mixing between the injected water and the reactants.

B. Integration & Demonstration

To demonstrate the actuators, we show how they can be designed for the two use cases presented in Section I. Firstly a simple locomotion system for agricultural applications, and secondly a small ingestible actuator. Although these are only preliminary demonstrations, they highlight the capabilities of the soft actuators.

a) Locomoting System: By integrating two actuators around a cylindrical body, the actuators can be used to periodically trigger rolling. Fig. 10 shows the robot developed using the actuators and pictures of the actuation system. The actuation is limited, and the locomotion is slow (approximately 180 degrees of rotation per 30 seconds) but this demonstrates the ability to combine the actuators to create systems which show locomotion.

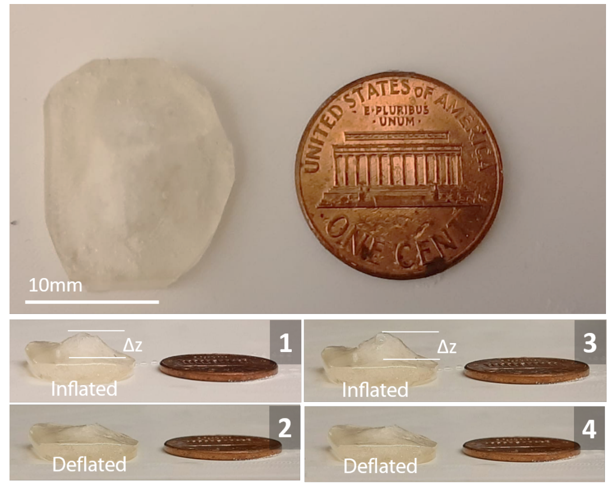

Fig. 11: Top) Small scale actuator shown next to a 1 cent coin for scale. Bottom) The actuation cycle for the small ingestible actuator.

b) Small Ingestible Actuator: Here we show how the actuators can be scaled down to create swallow-able ingestible actuators which could assist navigation through the human body, for example to release drugs, or carry small sensors. We demonstrate how the actuator size can be reduced to that closer to a pill. Fig. 11 shows an actuator and the periodic actuation which can be achieved.

C. Biodegradability

Due to the properties of the gelatin/glycerol materials after use the actuators can be reused or can be left to degrade. When left in the correct conditions, they will naturally begin to degrade. Additives could also be used to increase this rate of degradation. This property is beneficial for both the use cases considered.

For ingestigable robots the ability to degrade within the body could allow them to release drugs in a targeted manner and for the actuator to pass through the body safely. For agricultural applications, the ability for a system to biodegrade in the soil allows for many robots to be deployed without littering of the environment.

Fig. 12 shows timelapse pictures of the two actuation systems (locomotion and ingestible actuator) placed in water maintained at 50^0C. Both actuators degrade in less than 20 minutes, with the smaller actuator taking a shorter amount of time to degrade. Although the temperature accelerates the process, this demonstration highlights the degradable nature of the actuators.

V. DISCUSSION & CONCLUSIONS

The actuation method presented provide a simple method of generating controlled actuation through physical programming. When combined with the biodegradable and re-useable materials, this method was used to generate untethered degradable actuators. After untethered use the actuator can naturally degrade. Although this work presents only an initial

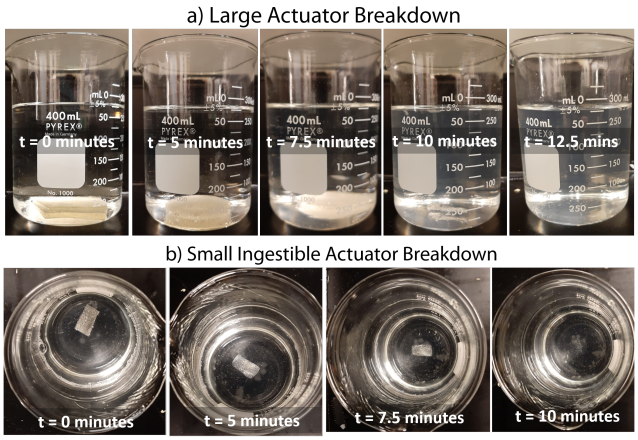

Fig. 12: Process of biodegradability of the actuators when placed in water at 50^0C. Top) Large actuator as used in the rolling system, Bottom) Small ingestible actuator.

investigation of the technology, it provides new methods and materials for future development.

The development of entirely soft, untethered robotic components and actuators is an important goal to enable new and exciting robotics technologies. Although current technologies in this area show poorer performance for traditional metrics such as force, repeatability, reliability and range of movement, the capabilities of such new technologies enables new applications. For the actuator technology shown in this paper we show how the functionality of degradability and mechanical programmability provides opportunities in both medical and agricultural applications.

To develop the actuators further in to robotic systems with full functionality, methods of developing more complex mechanical programming must be investigated. This could be used to create sets of actuators which allow for higher force systems or actuators which allow controlled bending or multiple-stages of movement. Additionally it is necessary to optimize the use of the chemical reagents to stabilize the rate of the reaction and to extend the useful life time of the actuator.

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