Passive, Reflex Response Units for Reactive Soft Robotic Systems

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***Abstract*—As robotic systems enter an ever expanding spectrum of industries, it is becoming increasingly important that they are built to respond quickly and efficiently to dynamic environments. This paper presents a passive, reflex response (PRR) unit for quick actuation of pneumatic soft robotic systems. The PRR unit consists of a pressure reservoir with a soft one way valve that can be opened by passing a pin through its aperture. The device is mechanically stimulated by the environment, leading to the release of stored pneumatic pressure into the body of a soft robotic system. Prototypes of the PRR unit were characterized with three different valve sizes (6 mm, 9 mm and 11 mm) across a range of reservoir pressures (0.2 bar to 1.2 bar). A pin, attached to a load cell, was then lowered into the valve aperture until it opened. Force and pressure dynamics were recorded, along with the curvature of a pneu-net bending actuator during successive testing of the unit when coupled with a soft structure. For all valve sizes, the force required to open the valve increased proportionally with increasing internal pressure, with a minimum force of 0.98 N and a maximum force of 4.68 N. Time to vent the system decreased with increasing valve size, from 1.30 s to vent the system with the 6 mm aperture at 1.2 bar, to 0.53 s to vent the system with an 11 mm aperture. When integrated with a pneu-net bending actuator, the force required to open the 11 mm aperture increased to 15.82 N when charged to 0.5 bar of internal pressure due to the added force required to push on the constraining layer of the pneu-net. The PRR unit actuated the pneu-net in 0.37 s when charged to 0.5 bar of internal pressure. This demonstrates how reactive soft robotic systems can rapidly respond to mechanical environmental stimuli without the need for high-level control.**

***Index Terms*—Soft Sensors and Actuators, Perception for Grasping and Manipulation, Perception-Action Coupling**

I. INTRODUCTION

FOR robotic systems to adequately traverse or interact with dynamic environments, it is crucial that they are able to react quickly to changes in their surroundings. In 2014, the DARPA Robotics Challenge was held to test the state of the field for disaster response robotics [23]. The competing teams were tasked with overcoming challenges in known locations in an environment that was hazardous, but not dynamic. A key outcome from the competition was the robot's over-reliance on high level computation when responding to their environment. Consequently, none of the robots were able to react to error or change without first processing visual and localisation data before calculating a response. This conventional sense-plan-act framework is not time efficient and is in stark contrast to the multitude of reflexive systems found in nature.

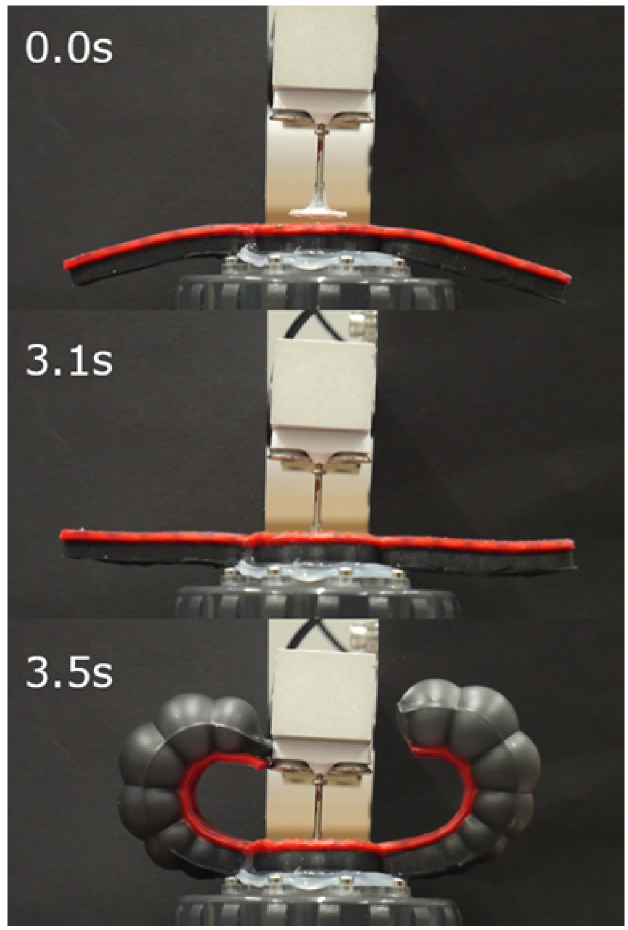

Fig. 1. Activation of a PRR unit. After 3.1s the force of the linear actuator is sufficient to trigger the PRR which then fully inflates the coupled pneu-net in under 0.5s.

Biologically, reflexive actions can be advantageous as they bypass the need for high level input from the brain, making the reaction to a stimulus much faster [8]. Within the natural world, a plethora of such reflexive systems exist, such as the Venus flytrap capturing its next meal via a buckling instability [5], an ant climbing a wall by a 'preflexive' reaction within it's pre-tarsus [4] [3] or the palmer grasp reflex a new-born baby uses to grip its mother's thumb for support [17] [6]. The addition of such mechanisms to robotic systems may increase the robot's ability to respond to mechanical stimuli

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The data supporting this paper is available upon request from the author in its environment while also reducing the need for high level control.

Soft robotics provides an exciting new perspective from which to tackle this challenge. Exploiting predominantly compliant materials, it is possible to create novel structures with a high number of degrees of freedom. This reduces the need for high level control by embodying intelligence into the structure of the robot, known as morphological computation [15].

However, the field of soft robotics presents its own challenges, as many of the systems developed (in particular those reliant on pneumatic elastomer networks) remain tethered to external components such as air compressors and networks of valves [20]. Additionally, the speed at which soft robotic systems can actuate is currently limited by the input. With pneumatic systems in particular, the speed at which a system can actuate is dependant upon the pump or compressor that is driving it [7]. This is problematic for high speed responses, as they require tethering the system to a large compressor, thus the whole system becomes larger and difficult to manipulate.

For reactive soft robotic systems that can be mechanically stimulated by their environment, it is important that the developed system responds rapidly to contact. In 2019, Thuruthel et. al presented work on a bistable gripper with embedded sensing that allowed it to snap through to a closed state when contacted by an object [18]. This system was very effective and provided a good solution to creating an untethered system that could respond quickly (with actuation time of 0.021 seconds), however, it was non-reversible and required a user to reset the system upon actuation. Similarly, Kim et. al and Chen et. al both developed mechanisms that utilise shape memory alloy (SMA) to provide a fast, bistable, snap-through, but neither system was reversible [9] [1].

Other methods that have been developed to achieve high speed include the use of dielectric elastomer actuators (DEAs) [21] [2], and combustion [10] [19]. However, DEA technologies rely on high voltage inputs to actuate and combustion based robots can be unpredictable with respect to direction of travel and repeatability of locomotion [20]. Though some progress has been made with respect to control of combustion via integrated networks that operate as control loops [22].

Within this research, we propose the use of mechanically stimulated pressure vessels to act as passive, reflex response (PRR) units for pneumatic soft robots. The pressure vessels will be pneumatically charged and will actuate when an embedded pin is stimulated mechanically by the environment. By reservoiring pressure around the body of a robot, we allow for a system with a single pneumatic input that can have multiple outputs. It is also possible to trickle charge the pressurised chambers with low power pumps and still realise high speed actuation.

Within this paper, we present the design of the PRR unit, analyze the effect of the pressure vessel's volume and fluid pressure on actuator performance, experimentally characterise the force and pressure dynamics of the system for increasing internal pressures and demonstrate how the system can couple to a typical pneumatic network (pneu-net) [13] structure for quick actuation from an environmental stimulus.

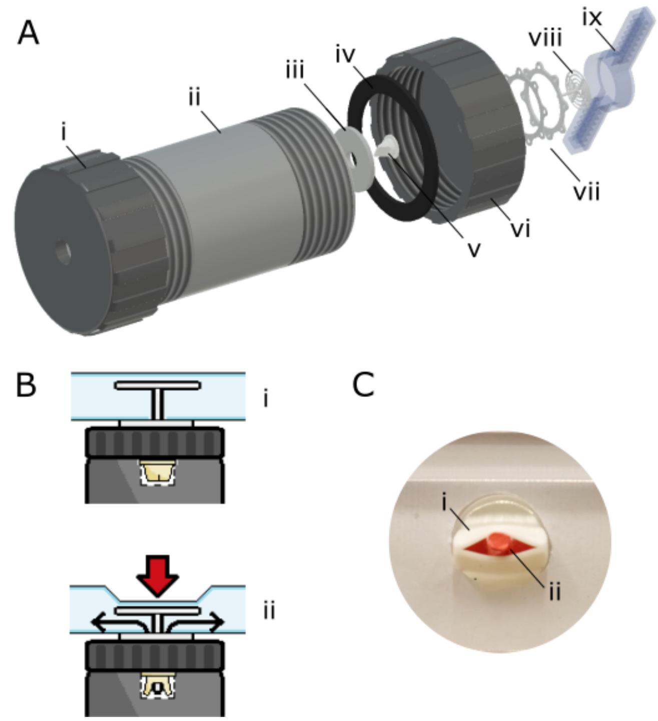

Fig. 2. Schematic of the PRR unit design. A) Exploded view diagram of the PRR unit. i) PVC threaded cap with hole for inlet. ii) PVC threaded pipe. iii) Acrylic disk for mounting the valve. iv) Rubber gasket. v) Silicone duck billed valve. vi) PVC threaded cap with hole for pin entry. vii) Mounting rings for the soft robotic actuator: one silicone to bond to the robot, one acrylic to mount to the cap. viii) 3D printed pin with flanged base to bond to soft robotic system. ix) Soft robotic actuator, in this instance a pneu-net. B) Principle of operation of the PRR unit. i) The system is combined and sealed with screws and silicone adhesive (with cut away to view valve). ii) The system is stimulated by pushing the pin into the PRR unit and allowing air to flow into the pneumatic network within the robot (with cut away to view valve opening). C) Front view of the valve mounted in the acrylic disk, with example of the pin opening the valve aperture. i) Soft valve. ii) A pin protruding through the valve aperture. A red pin was selected for clarity.

II. DESIGN AND FABRICATION

The PRR unit consists of three key parts: the pressure vessel; the valve; and a pin that is embedded within the body of the soft robotic system such that the pin is protruding towards the aperture of the valve and the base of the pin is aligned with the robot's surface (as shown in Figure 2). The system is mechanically stimulated through interactions with the soft robot's environment. By deforming the surface of the soft robot, the pin embedded under the surface is pushed through the aperture of a one way valve, allowing air to flow into the pneumatic network within the robot (as shown in Figure 2B).

The pressure vessel for the PRR unit is a closed pneumatic system capable of withstanding high internal pressure. For testing, the pressure vessel consists of a PVC threaded nipple (internal height 88 mm, radius 22.5 mm) with two threaded PVC end caps at either end (machined by Plastic Pipe Shop Ltd.) (see Figure 2A i, ii and iv). One end cap has been drilled and tapped to fit a threaded push in pipe connector for 6 mm tubing and the other has been drilled to allow access to the valve. Both the threaded nipple and the end caps are rated for 10 bar of internal pressure. PTFE tape has been used in all instances where threaded components are screwed into the body of the pressure chamber to ensure the system is airtight. A large pressure vessel with thick walls was selected for lab safety, however, it is possible to use smaller vessels constructed from different materials, such as fibre reinforced elastomer.

The soft valve design considered for use within the PRR unit is a duckbill one way valve (Standard Elastomeric Valve Components, Minivalve), with shore hardness 50A and cracking pressure below 0.005 bar (see Figure 2A v and C i). The duckbill valve design is capable of withstanding high pressures (up to 3 bar) and in this work it is demonstrated that it can be bypassed by passing a pin through its aperture. To characterise how aperture size effects the pressure and force dynamics of the PRR unit, three sizes of valve will be tested with aperture widths of 6 mm, 9 mm and 11 mm. Each valve has been mounted within an acrylic disk and then sealed to a threaded cap with silicone adhesive (Sil-poxy^{TM}, Smooth-On). Figure 2B and C display an example of how each valve aperture opens upon mechanical stimulation of the PRR unit. All components are commercially available and as such it is expected that the system will be long lasting and reliable.

The pin for the PRR unit has been designed with a 30 mm flanged base that extends into the body of the soft robot, providing a large surface to externally stimulate the unit, see Figure 2A viii. The base consists of three concentric rings, connected by thin beams such that, when embedded within the soft robot, the silicone used to secure the pin has multiple anchor points to hold it firmly in place. The pin itself is 2 mm in diameter and extends 30 mm, with a tapered end to conform to the shape of the valve.

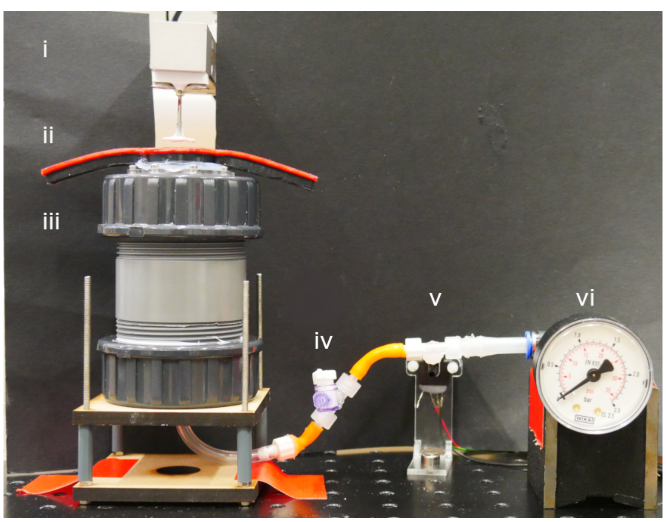

Fig. 3. The experimental set up for characterising the force required to activate the PRR unit. i) Load cell with rigidly attached 15 mm disc to stimulate the PRR unit. ii) Black pneu-net bending actuator with red constraining layer for image analysis. iii) The PRR unit. iv) Pneumatic input connection. v) Digital pressure sensor. vi) Analogue pressure sensor to provide visual feedback on the state of the PRR unit.

III. VALVE CHARACTERISATION

The PRR units will activate when a force is applied to a pin embedded within the soft robot, pushing apart the sides of the valve in the unit and allowing air to pass into the robot. To characterise this system, it is important to determine the relationship between internal pressure within the PRR unit and the force required to open the valve. To test this, a PRR unit without an integrated pneu-net was activated using a vertically mounted linear actuator. The linear actuator was used to move a 2 mm pin attached to a load cell down into the unit until the valve opened and the pressure was released to atmosphere (as in Figure 3 but without the integrated pneu-net). The PRR unit was pre-charged to a range of set internal pressures, from 0 bar to 1.2 bar in increments of 0.2 bar, and monitored with a digital pressure sensor (ASDX Series, Honeywell) and visually with an analogue pressure sensor (EN 837-1, WIKA). In this way, it was possible to determine how charging the unit to higher internal pressures affected the force required to open the valve. The test also allowed for comparison between the three valve sizes. By monitoring the pressure dynamics with time, it was possible to examine how quickly each valve released pressure and determine whether it is possible to tune the PRR unit for different applications by selecting a specific size of valve.

IV. INTEGRATION WITH SOFT SYSTEMS

Once integrated into a soft pneumatic system, the pressure dynamics of the system change as the unit no longer exhausts to atmosphere. Upon actuation of the PRR unit, air exhausts into the fluidic elastomer until the pressure in the pressure vessel of the PRR unit and the soft robot has equalised.

To investigate the relationship between pressure and volume within this coupled system, we can use the ideal gas law:

$$PV = nRT, \tag{1}$$

where P is the absolute pressure in Pascals, V is the volume in cubic metres, n is the moles of gas, R is the universal gas constant and T is the temperature in Kelvin.

If we assume adiabatic conditions then T, and therefore PV, remain constant. Thus, from the ideal gas law, the product of pressure, P_{PRR}, and volume, V_{PRR}, for the coupled PRR system at equilibrium (i.e. after the PRR valve has been activated) is given by:

$$P_{PRR}V_{PRR} = P_{pv1}V_{pv} + P_{atm}V_{a1}, \tag{2}$$

where pressure, P_{pv1}, and volume, V_{pv}, describe the initial state of the pressure vessel (V_{pv} is assumed to be fixed i.e. rigid pressure vessel) and the initial state of the actuator is assumed to be at atmospheric pressure, P_{atm}, with initial volume, V_{a1}.

The total volume of the PRR in its activated state, V_{PRR}, is the sum of V_{pv} and the final, inflated volume of the actuator, V_{a2}. With an approximated expression for V_{a2} in terms of activation pressure and with P_{pv1}, V_{pv}, P_{atm} and V_{a1} all known quantities of the system in its initial state, it is therefore possible to find the equilibrium pressure, P_{PRR}, of the coupled PRR system:

$$P_{PRR} = \frac{P_{pv1}V_{pv} + P_{atm}V_{a1}}{V_{pv} + V_{a2}}. \tag{3}$$

As the pneu-net in [14] was fabricated to exactly the same specifications as the integrated actuator that will be tested later in this section, the data from [14] can be used to show how the actuator's curvature and volume increase with pressure, as shown in Figure 4.

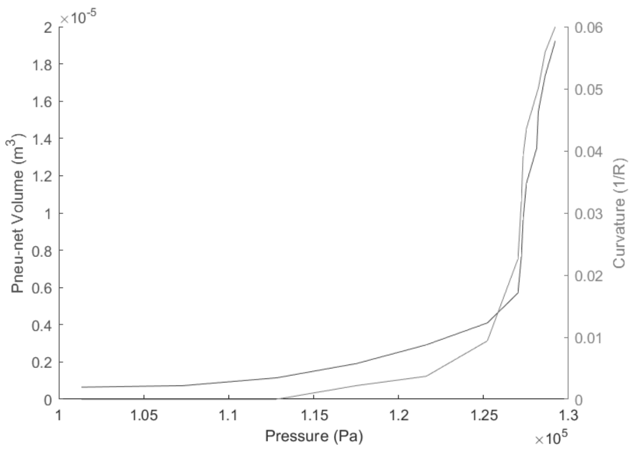

Fig. 4. Volume and curvature responses with increasing internal pressure for a test pneu-net.

To test how the integration of a PRR unit into a soft system affects the force and pressure dynamics, the test discussed in Section III was repeated with a PRR unit with 11 mm aperture valve that vented into a 134 mm by 12 mm, two channel pneu-net. The pneu-net is coloured black, with a red constraining layer to aid image analysis (see Figure 1). Internal pressures were set from 0.1 to 0.5 bar in increments of 0.1 bar.

To physically test the coupled system, the pin on the load cell was modified with the addition of a 15 mm disc to push against the pin embedded within the pneu-net (Figure 3 i). The pressure and force dynamics were monitored as in the previous test, as well as the curvature of the pneu-net. Curvature was calculated by conducting image processing on frames from a video taken of the experiment within MatLab (Mathworks). Red pixels were extracted from the image and translated to a point cloud, so that the CircFit function could be used to fit a circle to the edge of the pneu-net [14]. A total of 11 frames were taken from each video, from the moment the pin makes contact with the pneu-net to the moment the pressure equalises.

V. Results

A. Valve Characterisation

Figure 5 displays the pressure and force response of the PRR unit with the 11 mm aperture valve for increasing internal pressure. As internal pressure increases, the force required to open the valve increases linearly from 0.95 N of force to 4.63 N of force. This trend was true for all aperture sizes, although smaller valve apertures required less overall force.

In all cases, pressure drops instantaneously the moment the aperture is opened. As expected, higher internal pressures result in longer vent times. Again, this trend was true for all aperture sizes, but the smaller apertures had a much slower overall vent time as more of the aperture was blocked by the pin upon activation (which resulted in a quadratic increase

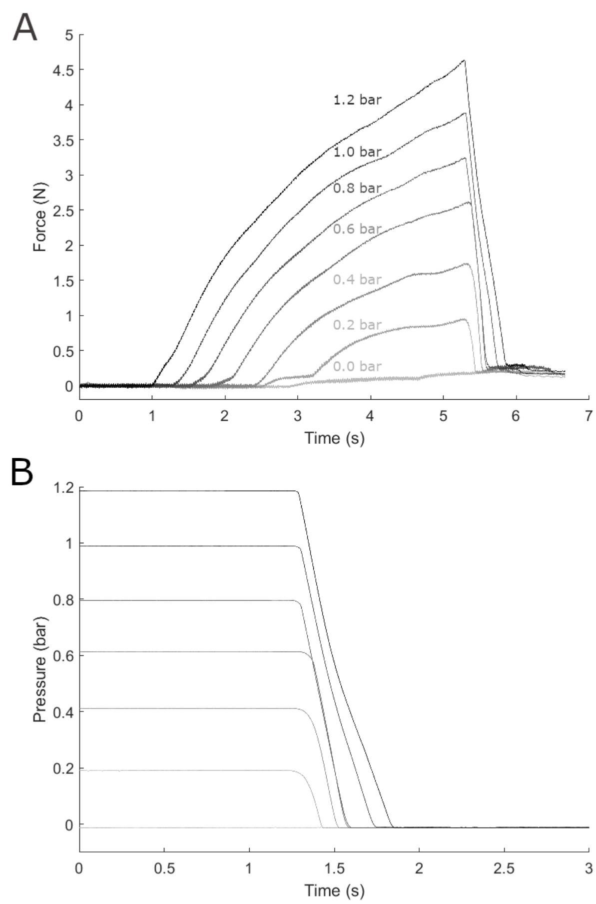

Fig. 5. The A) Force and B) Pressure responses for a PRR unit with an 11 mm aperture valve and internal pressure increasing from 0 bar to 1.2 bar by 0.2 bar.

in the time it took for the pressure to equalise). Figure 6 displays the results for all three aperture sizes. As shown, the force required to open the 6 mm valve at 1.2 bar of internal pressure is 3.54 N, with a vent time of 1.298s. For the 9 mm valve, the force required is 4.48 N, with a vent time of 0.640s and for the 11 mm valve the force required is 4.68 N with a vent time of 0.532s. It can be seen in Figure 6A that the force required to trigger the valve increases monotonically with internal pressure. This is because increasing air pressure in the PRR unit will compress the duckbill valve's aperture more, which adds resistance to the pin penetrating the valve.

B. Integration With Soft Systems

For the integrated system with pneu-net fluidic elastomer actuators, the pressure and force responses can be viewed in Figure 7. In Figure 7B, it is shown that the pressure response of the integrated system is similar to the previous system, but the final resting state of the system varies depending on the initial internal pressure of the PRR unit, as expected. Coupling these results with the model discussed in section IV, it is possible to determine the volume change and curvature of a coupled actuator based on the initial pressure within the pressure vessel. In Figure 7A, it is shown that the force required to open the valve increases linearly as internal pressure increases.

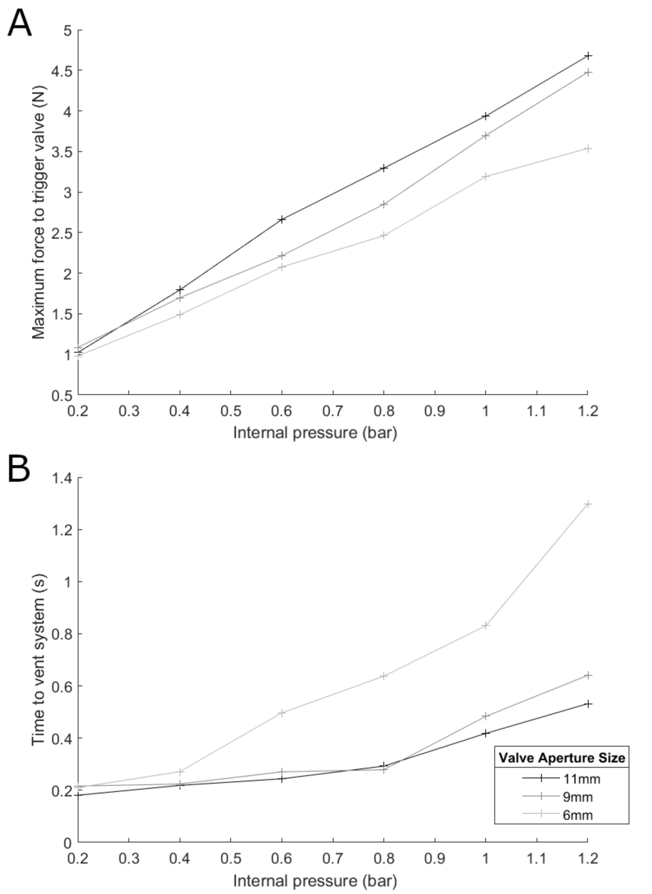

Fig. 6. A) Force required to trigger each of the three valves with increasing internal pressure. B) Time taken to vent each of the three configurations of PRR unit with increasing internal pressure.

However, the force required to open the valve has increased dramatically compared with the system venting to atmosphere, with a minimum force of 15.82 N at 0.5 bar of internal pressure. We believe this additional force is a result of the constraining layer that has been added to prevent the actuator from expanding. While it prevents the elastomer from bulging outwards, it also stiffens the point of contact, which makes it harder for the pin to be pushed into the aperture. However, the required force can be reduced by designing the constraining layer above the pin to be more soft and compliant.

A further test was conducted on a second pneu-net to investigate a more compliant constraining layer, where it was mounted such that the constraining layer was facing the PRR and the soft base was facing the load cell. Within this test, it was found that the force required to activate the PRR unit was 7.85 N of force at 0.5 bar of internal pressure and 3.92 N of force at 0.1 bar of internal pressure. This is half the force required to activate the previous pneu-net. However, as the pneu-net was unconstrained against the load cell it bulged outwards, resulting in a significantly reduced curvature. As such, a compromise between fully constrained and fully unconstrained could be adopted to decrease the force required to activate the PRR unit for certain applications.

While the force required to open the valve is currently quite high, having a range of force values means that it is possible to tune the coupled actuator and pressure vessel based on desired outcome. For example, if it is required that an actuator will only respond when impacted with a force greater than a certain amount, then a corresponding internal pressure can be selected to match that requirement.

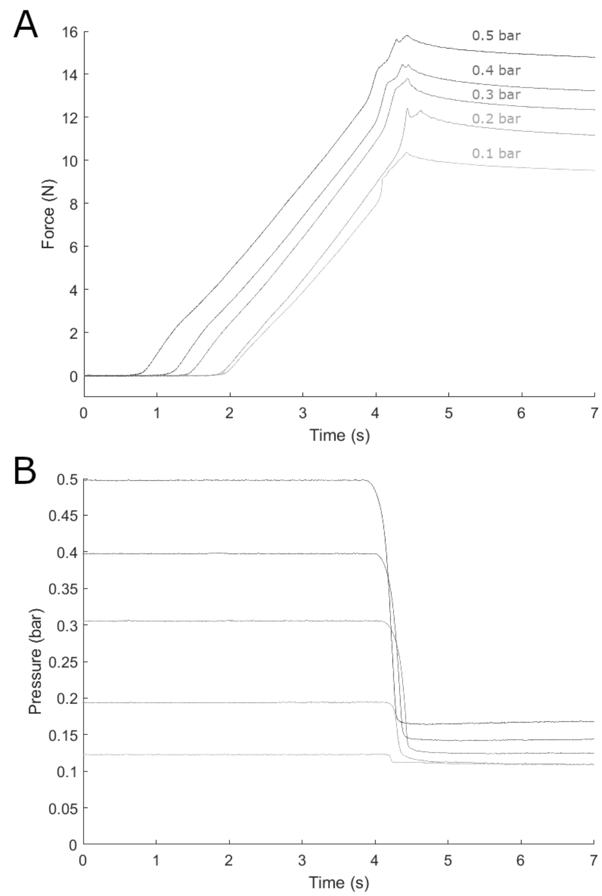

Fig. 7. The A) force and B) pressure responses for the coupled system, with 11 mm aperture PRR unit. Internal pressure increases from 0.1 to 0.5 bar in steps of 0.1 bar.

How quickly curvature stabilises for increasing internal pressures is displayed in Figure 8. There is a delay between activation of the PRR unit for different internal pressures as the linear actuator had to move further to generate a higher force to open the valve. For internal pressures of 0.1 and 0.2 bar, the final state of the pneu-net was not actuated enough to grasp (Figure 8C), however, they reached a stable final inflation in 0.17 and 0.4 seconds respectively. For internal pressures of 0.3, 0.4 and 0.5 bar, the pneu-net reached a curvature capable of grasping (Figure 8B). The time taken to complete actuation for each were 0.433s, 0.4s and 0.367s respectively. As before, having a range of response times and, in the instance where the PRR unit is coupled to a bending actuator, levels of curvature, it is possible to tune the unit based on the desired outcome. This will allow devices to be pre-programmed based on their application and further decrease the need for high level control.

VI. DISCUSSION

Within this work, we have presented a device that can be coupled with soft systems to create a passively activated

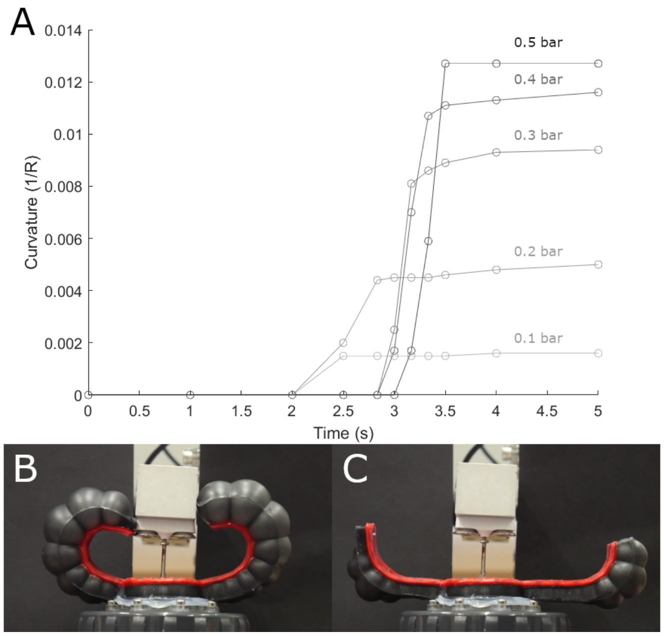

Fig. 8. A) Curvature of an integrated pneu-net during actuation of the PRR unit for internal pressures increasing from 0.1 bar to 0.5 bar in steps of 0.1 bar. Time starts from the moment the pin of the load cell meets the surface of the pneu-net and ends once the pneu-net has reached a stable final inflation. B) Final inflated state for 0.5 bar of internal pressure. C) Final inflated state for 0.2 bar of internal pressure.

response to an external stimulus. By adding such a mechanism to a soft robot, it becomes possible to react to a dynamic environment without the need for high level control, reducing the time it takes for the robot to respond. The device can be pneumatically charged by low cost, low weight pumps without affecting the speed at which it is able to activate.

As shown through the valve characterisation, it is possible to tune the PRR unit depending on the application. For applications where the stimulus will be high force and it is necessary to respond quickly, a larger aperture can be used with a high internal pressure. For applications where the stimulus is low force and the response can be slightly slower, a valve with a smaller aperture can be selected. It is also possible to tune the PRR unit by varying the internal pressure, thus making it possible to preempt environmental changes and make adjustments accordingly.

As previously discussed, a current challenge of this work is reducing the force required to actuate the unit when integrated into a soft system. It has been shown that by reducing the stiffness of the constraining layer of the soft robot, it is possible to reduce the force required for activation. However, this has the added effect of allowing the stimulus area to partially inflate under the pneumatic pressure. Future work will seek to overcome this challenge.

In the current study, the system was manually vented to depressurise. Future work will investigate the use of soft valves to incorporate digital logic (after Preston et. al [16]). In such a case, upon activation the PRR unit will re-pressurise to initial pressure, whilst the coupled system will maintain pressure. By adding a soft valve in the style of Preston et. al, we can use the logic within the valve to exhaust the actuator when the pressure in both parts of the system is high, resulting in passive, cyclic actuation.

An additional opportunity of the PRR design is the capacity for scaling the system size up or down by designing the vessel's volume and internal pressure. The prototype PRR unit used within this study was designed for the purposes of response characterisation and proof-of-principle pneu-net actuation. Hence, the internal radius of 22.5 mm and height of 88 mm were not designed for integration into a compact fully soft system. Future iterations of the PRR unit will utilise fibre reinforced elastomer as a pressure vessel, to create a fully soft unit.

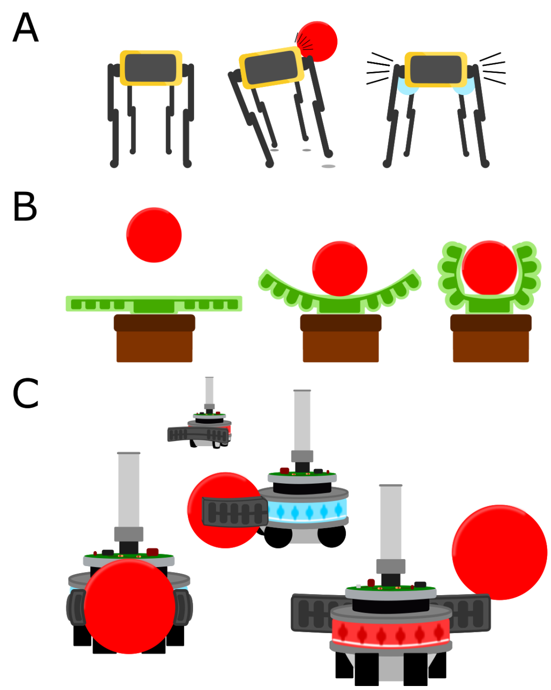

Fig. 9. Demonstrations of how to utilise the PRR units in existing robotic systems. A) PRR units act to stabilise a walking robot after it experiences lateral displacement due to impact. B) A biologically inspired, passive gripper that is able to capture objects it contacts. C) Swarm robots passively collecting items in an arena.

Overall, it is proposed that the addition of PRR units into robotic systems could lead to more responsive robotics that are better suited to working in dynamic environments. Figure 9 presents three examples of how the PRR units could be integrated into both soft and rigid robotic platforms. Figure 9A presents a legged walking robot that experiences lateral displacement due to an impact on its side. By integrating PRR units into the socket joints of the legs, it would be possible to stabilise the robot by pushing the legs outwards. Figure 9B presents a bio-inspired passive gripper that is able to capture objects it contacts. Figure 9C presents PRR units integrated into individual members of a swarm [12], such that the robots can collect items within their arena without the need for high level control.

Additionally, by connecting multiple PRR units, it may become possible to create systems with logic [16] [11], such that a single stimulus could trigger different actuation outputs based on strength and direction of the stimulus. Including the PRR units in existing soft robotic systems may also allow for multi-stage actuation. For example, integrating several PRR units into the fingers of pneu-net structures could allow for more adaptive and powerful grasps. As such, the future integration of PRR units into the body of soft robots will make it possible for robots to react to their environments and create more adaptive systems that further bypass the need for high level control.

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