# Soft Pneumatic Actuators for Legged Locomotion

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***Abstract*— Search and rescue robots are being used more frequently to access hazardous environments to assess situations and locate survivors. There are a wide range of existing mobile platforms for various situations and environments, but these robots are typically bulky, heavy or expensive, limiting their widespread and practical use in case of disaster mitigation. Also, like most robots, locomotive robots have explicit design criteria, subsequent physical parameters, and control schemes that do not leave much room for improvisation nor robustness on unknown environments. Unconventional silicone rubber-based soft pneumatic actuators (SPA) robots could offer an alternative actuation solution to such problems: these soft robots are adjustable, disposable, and easy to fabricate, naturally conforming to the unknown environment. In the paper, a palm-sized soft legged robot is proposed to verify the feasibility of such applications.**

## I. INTRODUCTION

Urban Search And Rescue (USAR) robots are becoming a familiar sight in disaster mitigations [1]–[3]. Especially in hazardous environments, mobile robots can be employed to assist rescue personnel to explore inaccessible areas and carry sensors to assess the situation [5]. One of the top priorities of such robotic systems is to examine the area to address the general situation and locate survivors. A large range of mobile platforms exist for various situations and environments, such as the wheeled or tracked mobile robots [3]–[6], unmanned marine or sea-surface vehicles [2], [3], or aerial platforms [2]. These robots are typically bulky ($> 300$ $mm$ in length) and can weigh over 30 $kg$ [4], [25], [26]. Most challenging areas for both rescue workers and robots alike are unseen and unknown terrains that have unexpected geographic shape due to explosions, landslides, or avalanches. Due to the complexity of the terrain, unknown route, inconsistent surface or material properties of the land, robots that have alternative locomotive systems with a higher dexterity are highly desirable [7]–[9]. Inspired by biological systems like snakes and inchworms, these systems are typically modular in design and densely packed with miniature electromechanical actuators and transmission mechanisms. However, consequently, precise modulation of each degree of freedom becomes challenging, especially in the unknown environment as mentioned above.

Alternatively, would it be possible to design a locomotive robot without knowing the dynamic model nor the terrain? If so, the robot itself must be small, cheap and light enough to be distributed in large spaces (to increase the odd of finding what / who is lost) while having a robust control scheme that allows it to confirm from flat ground to unexpected crevices with varying sizes. Modular soft robots with highly flexible and conformable actuators show potential for such applications. In this paper, we present a soft-legged robot prototype with high flexibility in both hardware and software due to the construction and components of the robot. The soft pneumatic actuators (SPAs) [10]–[13] that are employed here are fabricated almost entirely out of highly compliant elastomers such as silicone rubber or PDMS (Polydimethylsiloxane). These actuators are highly customizable while simultaneously being lightweight and compact; SPAs weigthing less than 15 $g$ are capable of producing force more than 30 times its own weight [12]. A particularly notable characteristic of the SPAs in the context of designing a machine for an unknown operating condition is their inherently low stiffness. Their ability to easily conform to surroundings may be an ideal characteristic to have during navigation through rubble, and it might also simplify the control scheme by eliminating the need for position/force control [11]–[13]. Moreover, the easy fabrication process and low manufacturing cost allows disposable and readily replaceable USAR modules.

In order to investigate the possibility of using alternative and unconventional actuation for the design of a USAR robot, we present an early design of an SPA-based, lightweight ($<$ 100 g), compliant, and disposable search and rescue robot (Fig.1). A proof-of-concept soft robotic

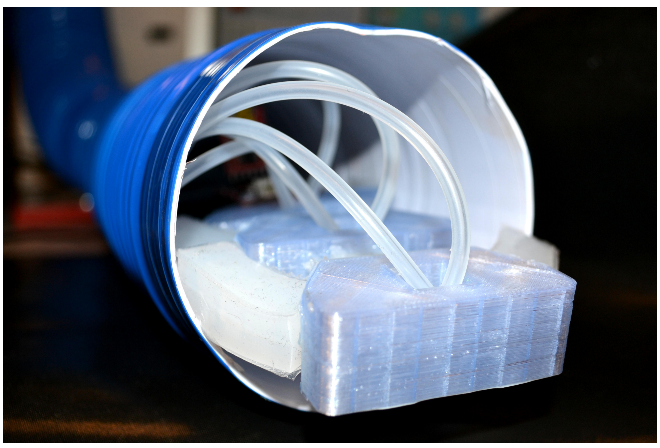

Fig. 1. Disposable search and rescue robot in a representative scenario

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system is developed to address the possibility of using SPAs for locomotion in tight spaces. Several earlier designs and operation modes are presented and compared with the current design evolution. The presented robotic system is envisioned to complement existing, established, rugged and expensive mobile platforms [1]–[6].

## II. SOFT PNEUMATIC ACTUATORS

Traditional actuators such as electric motors and internal combustion engines have been dominating both the industrial and academic world. However, certain applications require actuation to be lighter, smaller, or faster, which leads to the demand of alternative actuators such as piezoelectric unimorph actuators [14] or shape-memory-alloy (SMA) joints [15]. These actuators show clear advantages over the conventional motors in terms of scalability.

Soft Pneumatic Actuators (SPAs) are made of soft materials such as silicon rubber, and actuated by compressed air. Therefore, SPAs are inherently soft and vastly customizable, and are a viable alternative to conventional actuators [10], [11]. The fact that SPAs are easy to fabricate opens opportunities for customization. Several types of SPAs have been proposed, including: linear actuators, bending actuators, rotational actuators and multi-modal actuators amongst others [10]–[16]. In this paper, linear SPAs are used to achieve the desired actuation and locomotion of the robot.

The procedure to fabricate a linear SPAs [10] is shown in Fig.2. To make a linear SPA, two blocks of silicone-rubber (Ecoflex 00-30, Smooth-On Inc., tensile modulus of 69 $kPa$) are molded to form air chambers inside. With the silicon tube attached to the air source, the actuator inflates when pressurized. To fabricate the actuator, we first make the molds (Fig.2-A). These are 3D printed (HP Designjet 3D). The material for the molds is Acrylonitrile Butadiene Styrene (ABS). Next, we mix the Ecoflex A and B solutions in equal parts using a centrifugal mixer. Then, the mixture is inserted into the molds and degassed in a vacuum chamber. Afterwards the molds are put into an oven at 70 $^{\circ}C$ to cure for about 40 min (Fig.2-B). This results in two actuator halves that are attached together by a layer of liquid silicon. A tube is attached to the actuator at one end, resulting in the complete linear SPA (Fig.2-D).

The linear SPA produced here is 34 $mm$ long with $8 \times 8$ $mm$ cross-section area. Each actuator weighs 7 grams. It can withstand up to 40 $kPa$ of pressure before failing. It can generate up to 45 $mm$ of free displacement and 17 $N$ of blocked force. There are a number of design parameters affecting the SPA performance, such as the size of the air chamber, the thickness of the elastomer around it, the overall form, the length of the tube used to feed the air, and the number of chambers amongst others. A guide to choosing the key geometric features in order to obtain different mechanical properties for linear and other types of SPAs is in preparation.

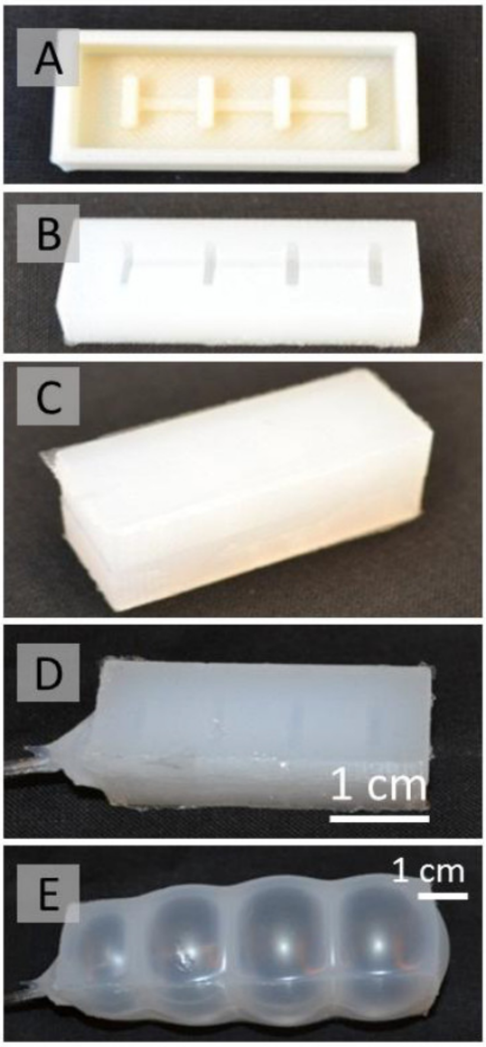


Fig. 2. The procedure of fabrication of a 4 chamber linear SPA. (A: the molds for making the linear SPA; B: the cured silicon rubber (half of actautor); C: The two halfs bonded together with silicon glue; D: finished linear Actuator; E: Inflated Linear Soft Pneumatic Actuator.)

## III. CRAWLER DESIGN

Researchers have used the customizable, conformable and disposable aspect of these actuators to produce different movements or gaits for mobile robots by adapting the design to generate new forms of actuation: jumping gaits powered by explosion [16], bio-inspired caterpillar crawling [17] and rolling soft robot [18]. This paper proposes a new bio-inspired actuation applied to a small, simple, mobile robot that could, for example, be used in disaster mitigation scenarios.

### A. *Bioinspired Design*

Organisms are filled with pipes and pumps to allow fluids to move along their bodies. These fluids either produce propulsion or just move around cells necessary for life. Many organisms use peristaltic tonus differentials to deform their shapes. In our design, each actuator is a soft tube that uses deformation in several directions to push against the surrounding environment. Our gait is similar to that of an inchworm, but with six legs, that alternate pairwise to crawl forward. This mixed design, allows redundant actuators to compensate for uncontrolled deformation and uncertainties in the friction behavior between the ”leg” and the ”floor”.

Previous walking robots with pneumatic soft actuators differ in their structure and locomotion modes. In [27], two types of walking robots are presented. One is a ”straight leg” robot which keeps its feet under its body, like mammals, and the other is an ”overhang leg” robot which keeps its feet well out to the side of the body, like reptiles. The mammalian-type robot is about 1 $g$ in weight and 15 $mm$ in length and is intended for pipe inspection and maintenance. The reptiliform robot is 1.5 $g$ in weight and 15 $mm$ in length. A 10 $kg$ and 700 $mm$ version of this robot was developed by the same group and reported in [27]. As a reference, in [28] another soft multigait robot was presented in [11] that can lift its trunk while advancing forward.

The aim of our new design is to verify the feasibility of soft actuators to develop simple USAR robots and to cover the small and dangerous environments that are unstructured *ergo* too difficult to use traditional searching rescue platforms. To meet the requirements of disaster mitigation applications, the robot needs to be small, light, replaceable and disposable. The robot must be able to go through different kinds of spaces, such as unstructured environments and tubes. Since the maximum measured force slope with these linear SPAs is about 22 $N/s$, and assuming only 30% efficiency and a duty cycle of a third of a second, we computed that the the maximum weight of the robot with external functional hardware (pumps, valves, sensors) external to the body weight should be below 100 $g$.

As shown in Fig. 3, the proposed robot design is composed of three parts: the actuators, the backbone modules, and the soft joints. The actuators are attached to the air source that provides compressed air. When extended they come in contact with the surrounding environment and the reaction force pushes the robot forward. They are positioned with a 135 ° deviation from the axial direction of the robot to avoid blocking with the environment while actuated symmetrically. Optimization of this angle, as well as other morphological changes, could result in improved locomotion speed. In future works, we will address these topics. The backbone modules are used to support the actuators and will also be used for integrating components. They are 3D printed using ABS. As a supporting structure, it needs to be as light as possible; therefore, it is printed with the lowest resolution and filling rate, resulting in a honeycomb internal structure. In the future, each module is expected to contain functional components and to be covered in soft materials. The soft joints connecting each module are made of silicon rubber in order to compensate for possible asymmetry in linear SPA actuation.

The complete robot is shown in Fig.1. It is 120 $mm$ long, 110 $mm$ wide, and weighs approximately 96 $g$. The tubes are attached to the air source, which provides the energy for locomotion. By sequentially inflating the three modules the robot will be able to crawl forward by interacting with neighbouring surfaces. Control of the gait and air pressure is performed through a pneumatic system.

### B. Pneumatic System

The pneumatic system used here is composed of two parts: the air source and the control system. A schematic of the complete system is shown in Fig.4.

The control system includes a pressure regulator for each front leg and another for the four legs in the middle and rear body. The desired pressure is sent through a DAQ (National Instruments) as analog voltage to the regulators. An activation signal is sent to 6 solenoid valves, depending on the duty cycle and the period of the locomotion cycle. The response time of the actuator is 100 $ms$ for pressures lower

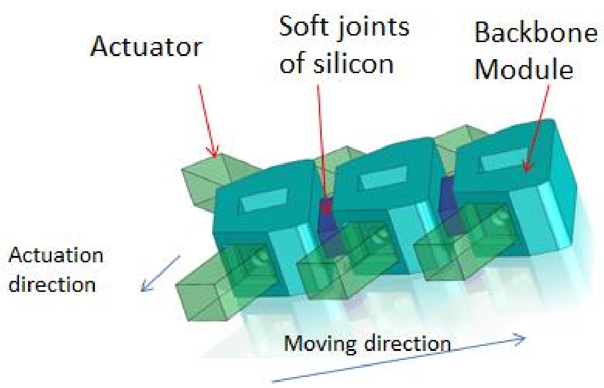


Fig. 3. CAD model of the robot

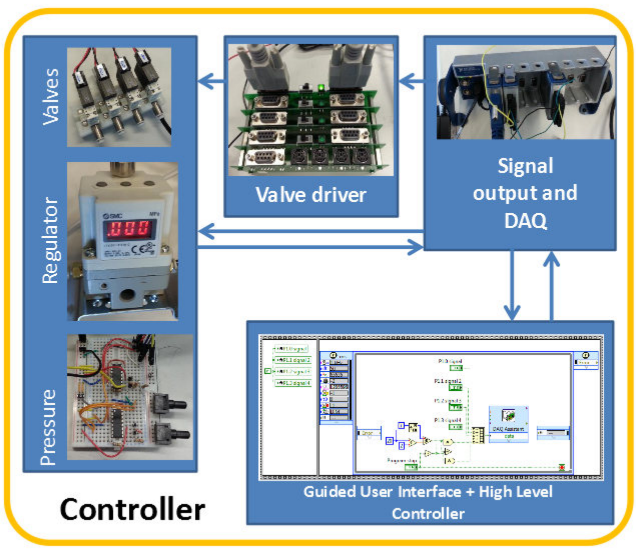


Fig. 4. Schematic of the pneumatic system

than 20 $kPa$. For pressures at the range of $20-30$ $kPa$ the response time is about 200 $ms$. The experimental setup used for characterizing this response time is the same used for bending actuators reported in [12]. The desired pressure of the three regulators, the duty cycle are set through to a Graphical User Interface (GUI) programmed in Labview (National Instruments).

### C. Orientation Sensor

In order to control orientation of the robot, an 9-axis Razor Inertial measurement unit (IMU)(SparkFun) was attached to the rear module (see Fig.5) to use the AHRS[1] to obtain measurement of the yaw angle (with respect to earth's magnetic north) of the robot's body. The 3-axis Digital Compass IC from the IMU (HMC5883L from Honeywell Inc) theoretically allows 1 to 2 degrees accuracy at 160 $Hz$ output rate. The yaw angle is processed on-board using an ATmega328 (Atmel) microprocessor and sent out via a serial stream at 57600 Bauds to an external controller running a Labview Virtual Instrument (National Instruments) at 5 $kHz$.

One important note is that the definition of the axes in the AHRS differs from what is printed on the IMU board. The Z axis is pointing downwards, which means a rotation of the robot's head o in the clockwise direction is read as a positive value. The sensors were calibrated based on the procedure described in [19]. Even though the procedure allows to filter out some of the gyroscope noise, we experienced noise of about $\pm 2\deg$ in the measurements.

## IV. EVALUATION

To evaluate the feasibility of this early stage robot design, we tested some dynamic properties of the system in two scenarios: a structured (flat floor with walls) and unstructured (only the floor without the walls) environment.

[1]Attitude and Heading Reference System

### A. Propulsion by pushing against the walls

The set-up consists of a 110 $mm$ wide passage that is created by two blocks of wood ((Fig.6). To understand how different pressures and inflation frequencies can influence robot movement, we tested the robot at multiple pressures and frequencies.

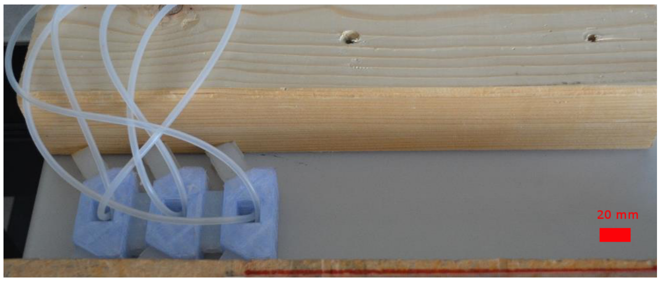


Fig. 6. The set-up used for evaluation of the propulsion capacity of the robot. The passage is 110 $mm$ wide.

The activation sequences of the three modules are shown in the duty cycle figure 7 for a frequency of 1 $Hz$. Initially, all of the actuators are inactive. Next, the two actuators on the front module begin to inflate. The middle modules start inflation at 33.33% of the period with the deflation of the first modules. The same event occurs for the rear modules, which start inflation at 66.66% of the period while the second module begins to deflate. The actuation pattern is inspired by the gait of an inchworm. However, instead of deforming one part of the body, our prototype inflates two actuators on each side of the body as symmetrically as possible.

TABLE I

AVERAGE VELOCITY

| | Pressure | | | | | |
|---|---|---|---|---|---|---|
| Frequency | 20 $kPa$ | 25 $kPa$ | 27 $kPa$ | 30 $kPa$ | 33 $kPa$ | 35 $kPa$ |
| 1 $Hz$ | 1 $mm/s$ | 5 $mm/s$ | 5 $mm/s$ | | | |
| 2 $Hz$ | 0.8 $mm/s$ | 7 $mm/s$ | 10 $mm/s$ | | | |
| 4 $Hz$ | | | | 4 $mm/s$ | 8 $mm/s$ | 4 $mm/s$ |

Using OpenCV, instantaneous and average velocity profiles were automatically extracted from video data of the

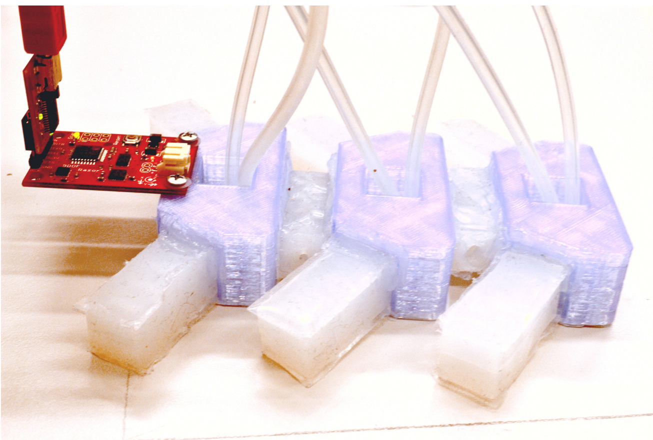

Fig. 5. Photo of the Robot with the Razor IMU attached at the rear end.

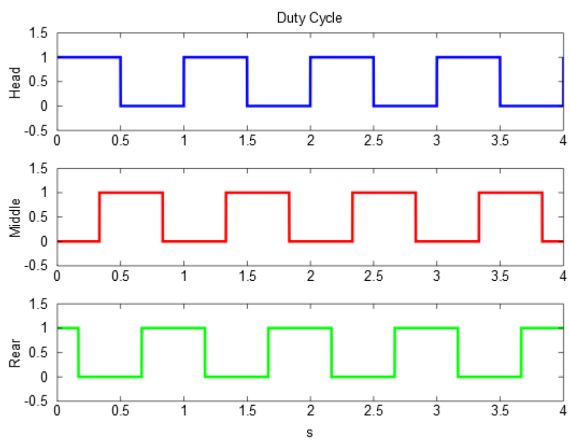


Fig. 7. Duty cycle of the three modules.

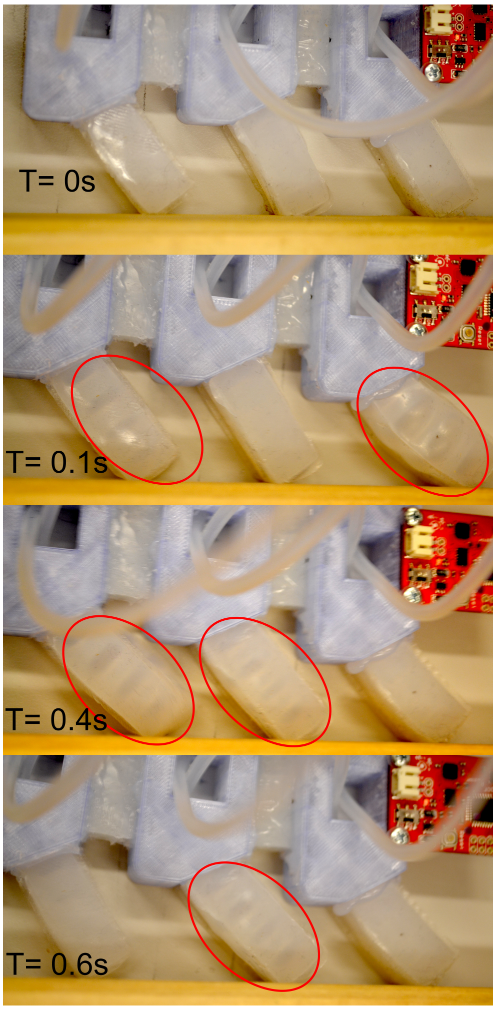


Fig. 8. Snapshots of the inflation pattern for one gait cycle (20 $kPa$, cycle period $1s$) The red circle represents the actuator that is inflating at the time.

crawler at several pressures and frequencies, by tracking the movement of the crawler, measuring the number of pixels moved per frame, and mapping this information to millimetres per second. The results in table I show that for the same frequency of activation the velocity increase by augmenting the pressure. Also, for the same pressure by, increasing the frequency the velocity also augments. These results suggest that, up to the point where no over-inflation of the actuators is attained, the overall velocity of the crawler is related to the flow rate of the air going into the chambers. The empty cases in table represent the cases where no measurable displacement of the crawler was perceived. For higher frequencies, if the pressure is too low, the air has no time to inflate the actuator enough to push against the environment and advance. This explains the empty cases for $4Hz$ for pressures of $20 - 27$ $kPa$ as well as the big drop in speed for the 20 $kPa$ and 2 $Hz$ case. For high pressures, at low frequencies, over-inflation of the actuators is reached and the crawler is blocked between the walls or lifted from the ground avoiding tangential propulsion. This is the case for pressures between $30 - 35kPa$ at frequencies of $2 - 4$ $Hz$. It also explains the drop of performance for the last tested case in the $1Hz$ and $4Hz$ frequencies. Certainly, a more thorough study on optimal period and pressure needs to be performed in order to find the critical pressure-frequency couple for a desired speed of motion, but in this paper we will concentrate on studying the effects of pressure (or pressure differentials) for locomotion and steering.

### B. *Propulsion on a flat surface*

A lot of variability in the behaviour of the robot is hidden by the fact that the environment is symmetrically disposed with respect to the body. In fact, this feature is an advantage of using soft actuators since very little control is needed to produce adaptation: ”behavior is not the outcome of an internal control structure only; computation is outsourced to body morphology and material properties” [21]. We decided to test the robot in the condition where no pushing off ”obstacles” in the direction of actuation is possible: in a flat surface. Then, the robot takes advantage of the inflation on the unprivileged directions to make contact with the terrain and advance thanks to the friction between the distal part of the actuator and the surface.

Several uncertainties come into play that make characterizing the friction between the actuator and the terrain a very difficult task. First, the inflation in the normal direction (with respect to the actuation direction) is not well modelled, since many chambers can come in contact with the ground. Also, the surface of the actuator can accumulate dirt, since the material is PDMS, and change the friction coefficient. In addition, the proximal part of the actuators is attached with silicon glue to the backbone modules. This introduces some uncertainty in the orientation of each actuator with respect to the transversal plane of the robot since some material is unevenly deposited between the body and the SPAs. Finally, other factors become more important in this situation such as fatigue and/or Mullins effect in the actuators, friction of the backbone module against the surface and pulling forces coming from the tubes.

The behaviour of the robot when the same pressure is applied to both front actuators is depicted in Fig.9. The propulsion pressure in the middle and rear modules is maintained constant at 25 $kPa$. This open loop behaviour reveals an asymmetry in actuation that provokes the robot to drift to one side regardless of the level of pressure applied. This irregularity may be attributed to various properties of individual actuators, including material aspects provoking fatigue or fabrication defects. In order to verify if the robot is steerable by pressure differential in the head actuators, we tested several combination of pressures and tried to roughly identify a pattern to steer the robot.

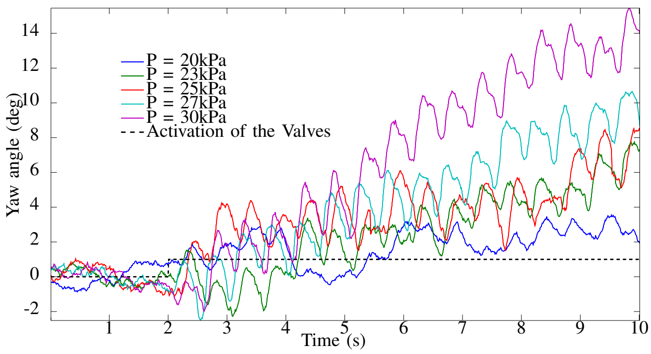


Fig. 9. Drift of the robot's yaw angle when identical pressure are applied to the front actuators. Here the robot advances without the walls, only by means of the friction between the actuator and the floor.

### C. Steering

If we apply a pressure differential on the frontal actuators, the robot is able to steer to the side with the lowest pressure. For example, in figure 10, a pressure of 27 $kPa$ was applied to the left actuator and 20 $kPa$ was applied to the right (while applying 25 $kPa$ to the middle and rear actuators in the same pattern described above to achieved forward propulsion). The result is a deviation of $8.7° \pm 1.7$ in the counter-clockwise sense.

In Fig.10, several combinations of pressures are shown. This allows us to roughly characterize the deviation of the robot's body with respect to the pressure differential in the front actuators. We can again observe the asymmetry that makes the robot drift to the one side when pressures are the same in both frontal actuators (black dotted line). We can then identify two distinct behaviours depending if the robot turns right or left:

- if the robot is to turn right then we can use the natural drift and apply the same pressure to both of the actuators. The higher the pressure, the higher the yaw deviation.
- if the robot should turn left, the simplest way of controlling the yaw angle is to apply 20 $kPa$ to the left actuator and augment the right pressure if we want to augment the deviation angle.

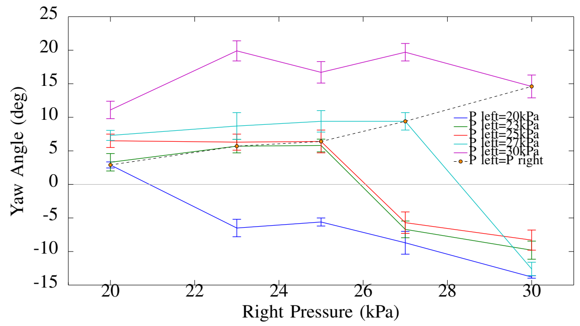


Fig. 10. Pressure combinations to achieve deviation (yaw angle). The black dotted line shows open loop drift when P left and P right are equal.

This conditions can be implemented in a control loop like in a gain scheduling strategy. The problem in this "model" is that there will be a deadzone between $-5$ ° and 2 ° that will remain uncertain.

### D. Control

There is no simple way to take into account all of the uncertainties or disturbances. One possibility is to implement a sensor-based robust control strategy. Such an approach has the advantage of avoiding most modelling of physical interaction between the robot and the environment, and takes advantage of an exteroceptive sensor measurement to regulate a variable. The term "sensor-based" is adopted because the measurement and control variable are both defined in the sensor referential [22]–[24].

One of the main advantages of soft actuators is that their compliance can absorb all the irregularities of the environment and the uncertainties of the model. This extrapolates into simplifying control since only simple modelling is necessary. A simple Proportional-Integral (PI) controller is sufficient in our case to control the yaw angle deviation.

This technique is suitable when uncertainties on the behaviour of the parameters are present. In our case, the inflation of each actuator is different and fatigue is an important factor. Also, the friction model of the distal part of the SPA in contact with the environment is not well known. This technique is the simplest way of implementing robust control. Using the knowledge we obtained from the open loop response, the PI-control can reject the natural divergence created by fatigued actuators. A controller with only Proportional action was tested prior to this solution. The controller was able to revert the deviation created by the deadzone discussed in the previous section but a static error remained.

Fig.11 shows the closed loop response to a desired yaw angle of $10°$ and then back to $0°$. The integral action acts from the start and there is no divergence in the yaw angle. For comparison purposes, the open loop response is added to the figure. It clearly diverges due to the asymmetry in actuation discussed in the previous section. The oscillation around steady state is due to the regulation effort and the fact that the propulsion is non-holonomic. This effect is also amplified because the IMU is attached at the tail of the crawler and the actuators that provide direction change are in the front. Also as stated before, the IMU readings present a noise of about $\pm 2°$. This effect is also visible in figure 9.

The tuning of the gains is done following the Ziegler-Nichols method [29] adjusted manually to obtain $K_P = 1.5$ and $K_I = 2$. The method has the advantage of being systematic and simple. By manual tuning, it is possible to achieve faster response but this implies a the need of a more comprehensive identification scheme. This defeats the purpose of outsourcing control issues to the structural compliance of the material. With a rise time $(10\% - 90\%)$ of around $5\ s$ and a settling time (to reach $10\%$ of final value) around $7\ s$, the crawler's performances may be sufficient as a proof of concept platform for USAR in unstructured environments. For information, the pressure used for propulsion on the central and back modules is $23\ kPa$ and the frequency used for switching between modules is $2\ Hz$.

## V. DISCUSSION AND FUTURE WORK

In this paper we introduced a new type of search and rescue robot which has the advantage of being versatile, easy to fabricate, and adaptable to different terrains. This first stage of design uses soft pneumatic actuators, rigid backbones, and elastic linkages. Since it is modular, the number of limbs can easily be increased, allowing redundancy in locomotion and more volume inside the body to carry a load (*e.g.* embedded electronics, pumps, and sensors). A two dimensional hexapod was presented as a first prototype servoed by a simple feedback control loop to account for model uncertainties in the model of propulsion and the behaviour of the actuators. This robot cannot overcome large obstacles but can crawl in uneven terrain based on the friction between the distal part of the actuator and the environment, and on the compliance of the backbone structure.

There is room for several optimization in the morphology of the robot. The positioning angle of the actuators could have a big influence on locomotion efficiency. The fabrication procedure of the actuators could also be improved to make them more consistent and less susceptible to fatigue or Mullins effect. Nevertheless, this paper constitutes proof that with a simple manually-tuned controller, complex

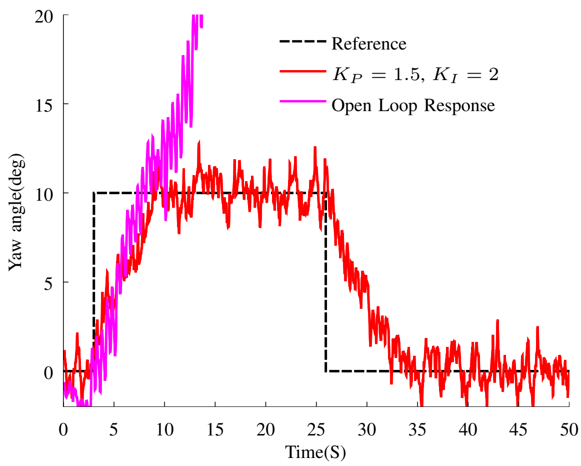


Fig. 11. Closed loop yaw angle response with a Proportional Integral controller. The open-loop response is drawn in magenta for comparison purposes.

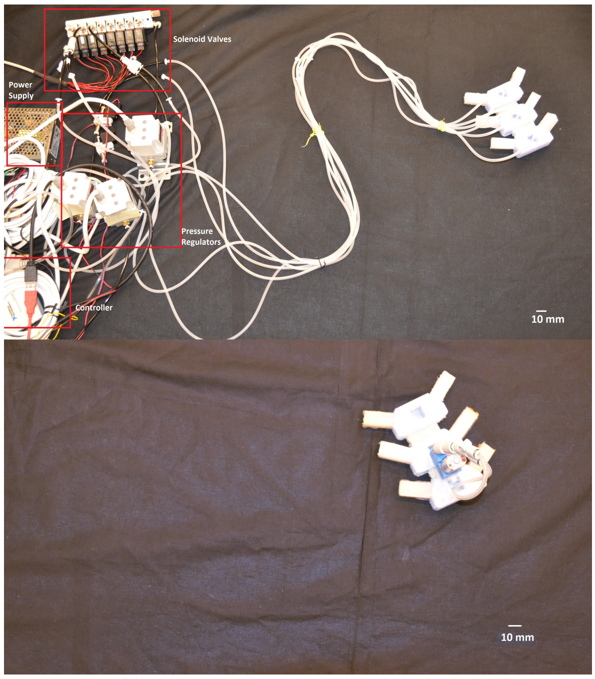


Fig. 12. Up: Current set-up including the robotś and pneumatic system (pumps, servo valves, pneumatic driver and power source). Down: Untethered version. For clarity only one module has the pump embedded.

locomotion can be obtained thanks to morphology and material properties of the actuators that accounts for many uncertainties in the model.

Clearly, the response can be improved with more sophisticated control strategies. For once, as an alternative, a robust fuzzy controller might enhance the response. In fact, by applying the knowledge collected in the open-loop response we implemented a sort of simple adaptable fuzzy rules.

Further work on this project include three primary paths:

- Embedding the pneumatic actuation system, sensing, and control electronics. The modular nature of the robot allows us to add more segments if necessary in order to embed all the systems on the body. Our vision is that the majority of the body should be made of soft materials. Right now the overall weight of the valves, pumps and electronics is about $380\ g$. In this prototype, we have not tried to optimize this feature. However, in order to avoid umbilical cords which are a major problem in disaster scenarios, we need to minimize the size and weight of the overall system. In fig 12, one pneumatic pump is embedded within one of the backbones to show the concept of the untethered system we want to achieve. The final goal is to have a self contained system using micro-controlled pumps and powered by light-weight Li-Ion batteries.
- Robust control of the locomotion. The uncertainties around the locomotion model are non negligible, especially the dead zone, and we plan to implement a more

robust technique.

- Navigation. Currently, we are using a Razor IMU to sense the magnetic field and have a measurement of the yaw angle which is the variable we are trying to control. We would like to move towards vision control to improve navigation properties intended for search and rescue purposes.

## REFERENCES


[1] Kruijff, G.-J.M.; Tretyakov, V.; Linder, T.; Pirri, F.; Gianni, M.; Papadakis, P.; Pizzoli, M.; Sinha, A; Pianese, E.; Corrao, S.; Priori, F.; Febrini, S.; Angeletti, S., "Rescue robots at earthquake-hit Mirandola, Italy: A field report," Safety, Security, and Rescue Robotics (SSRR), 2012 IEEE International Symposium on , vol., no., pp.1,8, 5-8 Nov. 2012

[2] R. Murphy, E. Steimle, C. Griffin, C. Cullins, M. Hall and K. Pratt, "Cooperative use of unmanned sea surface and micro aerial vehicles at Hurricane Wilma," Journal of Field Robotics, vol. 25(3), pp. 164-180, 2008.

[3] R. Murphy, K. Dreger, S. Newsome, J. Rodocker, E. Steimle, T. Kimura, K. Makabe, F. Matsuno, S. Tadokoro and K.Kon, "Use of Remotely Operated Marine Vehicles at Minamisanriku and Rikuzentakata Japan for Disaster Recovery," Proceedings of the 2011 IEEE International Symposium on Safety, Security and Rescue Robotics, Kyoto, Japan, pp. 19-25, 2011.

[4] W. Lee, S. Kang, M. Kim and K. Shin, "Rough Terrain Negotiable Mobile Platform with Passively Adaptive Double-Tracks and Its Application to Rescue Missions," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 1591-1596, 2005.

[5] Brunner, M., Bruggemann, B., Schulz, D. (2012, November). Motion planning for actively reconfigurable mobile robots in search and rescue scenarios. InSafety, Security, and Rescue Robotics (SSRR), 2012 IEEE International Symposium on (pp. 1-6). IEEE.

[6] K. Nagatani, S. Kiribayashi, Y. Okada, S. Tadokoro, T. Nishimura, T. Yoshida, E. Koyanagi and Y. Hada, "Redesign of rescue mobile robot Quince," Proceedings of the IEEE International Symposium on Safety,Security and Rescue Robotics, Kyoto, Japan, pp. 13-18, 2011.

[7] Mizutani, M., Maruyama, H., Ito, K. (2012, November). Development of autonomous snake-like robot for use in rubble. In Safety, Security, and Rescue Robotics (SSRR), 2012 IEEE International Symposium on (pp. 1-7). IEEE.

[8] Hamp, Q., Reindl, L. (2012, November). Soft robot concept for autonomous propagation in confined and obstructed environments. In Safety, Security, and Rescue Robotics (SSRR), 2012 IEEE International Symposium on (pp. 1-6). IEEE.

[9] Huff, J., Conyers, S., Voyles, R. (2012, November). MOTHERSHIP?A serpentine tread/limb hybrid marsupial robot for USAR. In Safety, Security, and Rescue Robotics (SSRR), 2012 IEEE International Symposium on (pp. 1-7). IEEE.

[10] F. Ilievski, A. D. Mazzeo, R. F. Shepherd, X. Chen, and G. M. Whitesides, "Soft Robotics for Chemists," Angewandte Chemie, vol. 123, pp. 1930-1935, 2011.

[11] Shepherd, R. F., Ilievski, F., Choi, W., Morin, S. A., and Stokes, A. A., Mazzeo, A. D., Chen, X., Wang, M., Whitesides, G. M.(2011). Multigait soft robot. Proceedings of the National Academy of Sciences, 108(51), 20400-20403.

[12] Sun, Y., Song, Y. S., Paik, J. (2013, November). Characterization of silicone rubber based soft pneumatic actuators. In Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on (pp. 4446-4453). IEEE.

[13] Song, Y. S., Sun, Y., Van Den Brand, R., Von Zitzewitz, J., Micera, S., Courtine, G., Paik, J. (2013, November). Soft robot for gait rehabilitation of spinalized rodents. In Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on (pp. 971-976). IEEE.

[14] Y. S. Song and M. Sitti, "Surface-tension-driven biologically inspired water strider robots: Theory and experiments," IEEE transaction on Robotics, vol. 23, pp. 578 - 589, 2007.

[15] J. K. Paik and R. J. Wood, "A bidirectional shape memory alloy folding actuator," Smart Materials and Structures, vol. 21, p. 065013, 2012.

[16] R. F. Shepherd et al., "Using Explosions to Power a Soft Robot," Angew. Chem. Int. Ed. 52, 2892-2896, 2013.

[17] Trimmer, B. A., Takesian, A. E., Sweet, B. M., Rogers, C. B., Hake, D. C., Rogers, D. J. (2006, May). Caterpillar locomotion: a new model for soft-bodied climbing and burrowing robots. In 7th International Symposium on Technology and the Mine Problem (Vol. 1, pp. 1-10). Monterey, CA: Mine Warfare Association.

[18] Marchese, A. D., Onal, C. D., Rus, D. (2011, September). Soft robot actuators using energy-efficient valves controlled by electropermanent magnets. In Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on (pp. 756-761). IEEE.

[19] Premerlani, W., Bizard, P. (2009). Direction cosine matrix IMU: Theory. DIY Drones.[Online][Cited: 1 7 2012.] http://diydrones. ning. com/profiles/blogs/dcm-imu-theory-first-draft.

[20] Y. S. Song, Y. Sun, Y. Bai, C. Suh, J. Condal Margarit, and J. Paik, "Static and Dynamic Properties of Soft Pneumatic Actuators", Submitted, 2014.

[21] Pfeifer, R., Lungarella, M., Iida, F. (2012). The challenges ahead for bio-inspired'soft'robotics. Communications of the ACM, 55(11), 76-87.

[22] Morel, G., Gangloff, J. (2005). Commande rfrence capteurs en robotique mdicale et chirurgicale. 5e Journes Nationales de la Recherche en Robotique, 131-142.

[23] J. Hill and W. T. Park. Real time control of a robot with a mobile camera. Proceedings of the 9th International Symposium on Industrial Robots, Washington, Dc, March 1979, pp. 233-246.

[24] Dhome, M., Richetin, M., Lapreste, J. T., Rives, G. (1989). Determination of the attitude of 3D objects from a single perspective view. Pattern Analysis and Machine Intelligence, IEEE Transactions on, 11(12), 1265-1278.

[25] Grand, C., BenAmar, F., Plumet, F., and Bidaud, P. (2004, April). Decoupled control of posture and trajectory of the hybrid wheel-legged robot Hylos. In Robotics and Automation, 2004. Proceedings. ICRA'04. 2004 IEEE International Conference on (Vol. 5, pp. 5111-5116). IEEE.

[26] Davids, A. (2002). Urban search and rescue robots: from tragedy to technology. Intelligent Systems, IEEE, 17(2), 81-83.

[27] K. Suzumori, E Kondo and H. Tanaka, Micro-walking robot driven by flexible microactuator, Journal Robotics and Mechatronics 5(6) (1993) 537-541.

[28] Suzumori, K. (1996). Elastic materials producing compliant robots. Robotics and Autonomous Systems, 18(1), 135-140.

[29] Ziegler, J. G., and N. B. Nichols. "Optimum settings for automatic controllers." Trans ASME (1942) 64-11.