Supplemental Information

A Resilient, Untethered Soft Robot

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Experimental Methods

To fabricate the body of the soft robot, we mixed batches of the rubber composite by blending 0.15 kg of hollow glass spheres, hgs (ρ_{hgs}~0.13 kg/L; Microbubbles; 3M) into 1.75 kg of M4601A silicone (ρ_{hgs} ~ 1.2 kg/L) using a rotational mixer and impeller blade. After mixing for 30 minutes, we added M4601B catalyst to the mixture at a 1:9 ratio of M4601B:M4601A by weight. After mixing for another 10 minutes, we poured the silicone over the laser cut mold.

Though foams are an option to reduce the weight of the body, silicone foam prepolymers are not (to our knowledge) readily available at lab scale, it is difficult to predict the final volume of foam expansion, and available foam prepolymers (e.g., urethanes) have been difficult to bond to silicone in our lab-scale processes.

Power Source Evaluation

We considered the use of compressed gas to power our pneumatic soft robot. Assuming isothermal expansion at temperature *T* (i.e. the process is slow enough for energy from the environment to heat the expanding gas), the maximum work *w* that can be done by *n* moles of gas at a working pressure, p_w, expanding to atmospheric pressure, p_{atm}, is given by Equation 1, where *R* is the Boltzmann constant.

$$w = nRT \ln \frac{p_w}{p_{atm}} \qquad \text{(Equation 1)}$$

For a working pressure of 16 psig (214 kPa), at 20°C, a mole of compressed gas has the potential to do 1.83 kJ of work. Compressed air at the commonly available pressure of 2,900 psig (20 MPa) and 20°C has a molar volume of 8.04 kmol/m^3. Pressurized carbon dioxide, however, is commonly at 850 psig (5.9 MPa), and has a molar volume of 17.8 kmol/m^3. Thus, the energy density of commonly available liquid CO_2 is approximately 2.2 times that of gaseous compressed air. Due to this higher volumetric energy density, we used CO_2 (l) as our source for compressed gas.

Using the Hagen-Pouiselle relationship (Equation 2) between pressure difference, ΔP, initial flow rate of gas into a Pneu-Net volume, Q, the gas delivery tube length, L, and radius, r, we calculated the theoretical flow rate for compressed gas from commercially available CO_2 cylinders. For compressed CO2 regulated to16 psig (214 kPa) flowing through a 1 m tube with a 2.5 mm radius, the initial flow rate is 0.12 m^3/s. However, this value will drop rapidly as the actuator begins to pressurize. The available volume of gas from a cylinder capable of holding 44 grams of liquid CO_2 (a size compatible with our larger robot design) is ~10.5 L at the working pressure.

$$\Delta P = \frac{8\mu L Q}{\pi r^4} \qquad \text{(Equation 2)}$$

Mini air compressors (MACs) are relatively light weight (< 0.5 kg) diaphragm pumps driven by electrical motors. They can be operated by electrical wire from a remote location, tethered operation, or via battery in untethered operation. While tethered (using thin/light copper wires), the robot can be actuated indefinitely. Two motors powered via a 3,200 mAh lithium-polymer (Li-Po; ~0.5 kg) can operate continuously for 1.6 hours (the motors draw ~1,000 mA of current each). However, the mini air compressors have limited flow rates: a maximum of 11 L/min (1.8×10^{-4} m^3/s) unrestricted, or 2 L/min (3.3×10^{-5} m^3/s) at 16 psig (214 kPa). Thus, over 1.6 hours, the volume of gas at the working pressure that the compressors deliver is at least 192 L.

Though the initial flow rate of gas into a Pneu-Net provided by the MACs is lower than for compressed gas cylinders, the overall volume of gas available for actuation is much greater (192 L vs. 10.5 L). In any case, flow rates quickly become limited by back pressure in the pressurized Pneu-Net. Combined with the potential for both tethered and untethered operation, MACs were the most attractive option for our untethered soft robot. The air compressors we ultimately chose (BTC IIS, Parker Systems) were a good compromise between cost ($297), weight (0.34 kg), size (7.5 cm length), and gas flow rates (2 L/min) at the chosen working pressure. It should be noted that a potential advantage of compressed gas is the ability to accelerate actuation with higher working pressures. However, this approach would require the development of materials and/or control systems capable of preventing material failures caused by steady-state exposure to such elevated pressures.

Table S1. Materials costs for the soft robot prototype.

Component	**Count**	**Unit Cost**	**Extended Cost**
Body materials			
Elastosil M4601 silicone rubber	3.5 kg	$21/kg	$74
Hollow glass spheres	0.3 kg	$150/kg ($75/gal)	$45
polyaramid fabric	12″x40″	$16	$16
Elastosil E951 silicone sealant	1 tube	$19	$19
Power and control components			
Mini air compressors	2	$297	$594
Valves	6	$43	$258
Custom Controller Board	1	$40	$40
Tubing and fittings	-	-	$20
Total			**$1066**

Controls

A custom, lightweight controller board was designed to control the miniature air compressors and solenoid valves that actuate the soft robot. A microcontroller (ATmega168, Atmel Corporation) on the controller board contained an Arduino bootloader for uploading, storing, and executing programs to control the soft robot.

We designed control programs to achieve two distinct modes of locomotion: an undulating gait and a walking gait (Figure S4, Video S2). The undulating gait consisted of repeated sequence of five states. 1) The rear leg PNs were actuated simultaneously for seven seconds (Figure S4 B). 2) the rear leg and body PNs were then actuated together for half a second. 3) The rear and forward legs, as well as the body PNs were all actuated simultaneously for five seconds (Figure S4 C). 4) The front legs were actuated alone for two seconds (Figure S4 D; the differential timing in actuation between the front and back legs of approximately five seconds biased the locomotion in the forward direction).5) Finally, all of the PNs vented to atmosphere for two seconds; the MACs were also turned off for this period to facilitate venting and conserve battery power (Figure S4 E).

A second program, consisting of four states caused the robot to execute a walking gait. 1) Beginning with all legs in contact with the ground (to prevent the robot from slipping backward), we caused the rear leg to actuate for four seconds, resulting in a “stance” position (Figure S4 H). 2) The actuated rear leg, as well as the front leg on the opposite side of the body, were then actuated simultaneously for four seconds to transfer both the pressurized air and the robot’s weight from the rear leg to the front one (reusing pressurized air during this transfer step increased the efficiency of the robot.) 3) The robot then thrust itself forward by both depressurizing the rear leg (allowing the stored elastic energy to straighten the rear leg), while continuing to pressurize the front leg to pull the robot forward over the course of four seconds (Figure S4 I). 4) Finally, all legs depressurized for half a second to prepare the robot for the next actuation cycle. Repeating the above four steps on alternating sides of the body resulted in our walking gait.

Figure S1. Systems diagram of the configuration of mini air compressors and valves used to drive the robot in undulation or walking gaits.

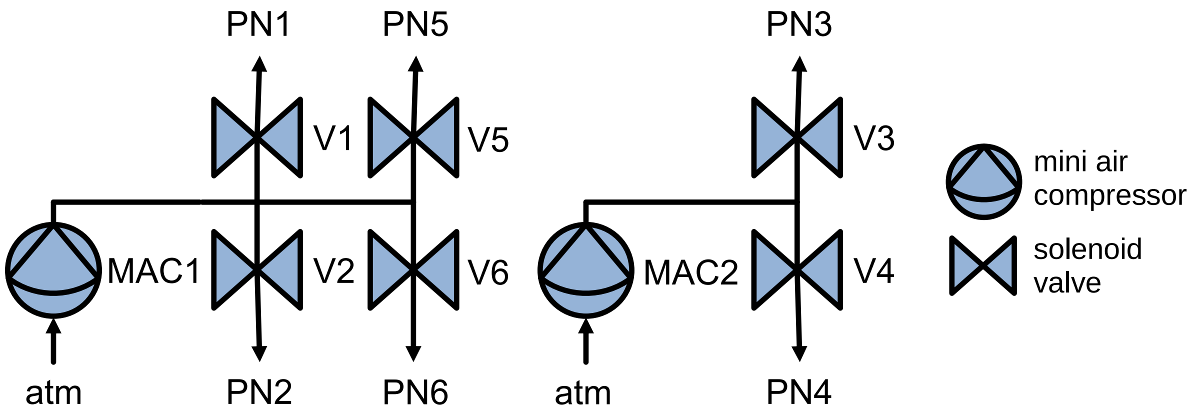


Figure S2. A The untethered robot design with the smaller tethered quadrupedal robot[7] placed on the interior for scale. The large robot is five times longer than the small one. **B** Mold used to replicate the large quadruped, composed of laser-cut acrylic pieces. **C** Layer 1 of robot cast in mold with waterjet-cut aluminum pieces inserted from the top (one aluminum piece removed from the lower-right leg is shown). **D** Replicated Layer 1 with molded features to increase surface area and improve bonding with Layer 2. **E** Cut polyaramid fabric being impregnated with elastomer to form Layer 2. **F** A patch of elastomer-impregnated polyaramid fabric added to the ends of the limbs prevents undesired expansion at these locations.

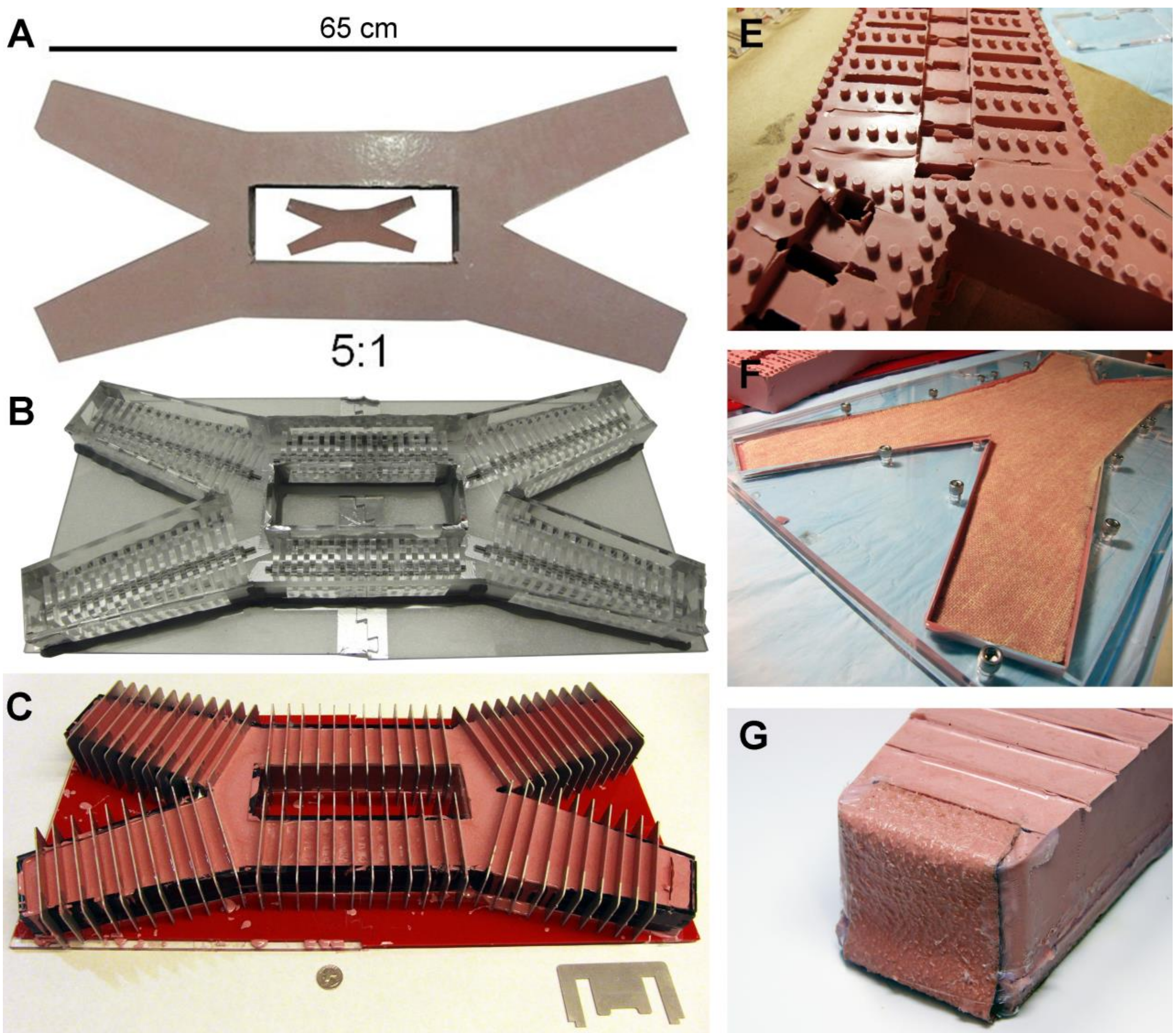


Figure S3. Maximum lift and hold tests. **A** Starting from a flat position, a tethered version of the soft robot was able to lift a mass of 3.4 kg (7.5 lbs) when actuated with a pneumatic pressure of 139 kPa (20 psi). **B** Starting from an actuated position with an internal pneumatic pressure of 139 kPa (20 psi), the robot was able to hold 8.0 kg (17.6 lbs).

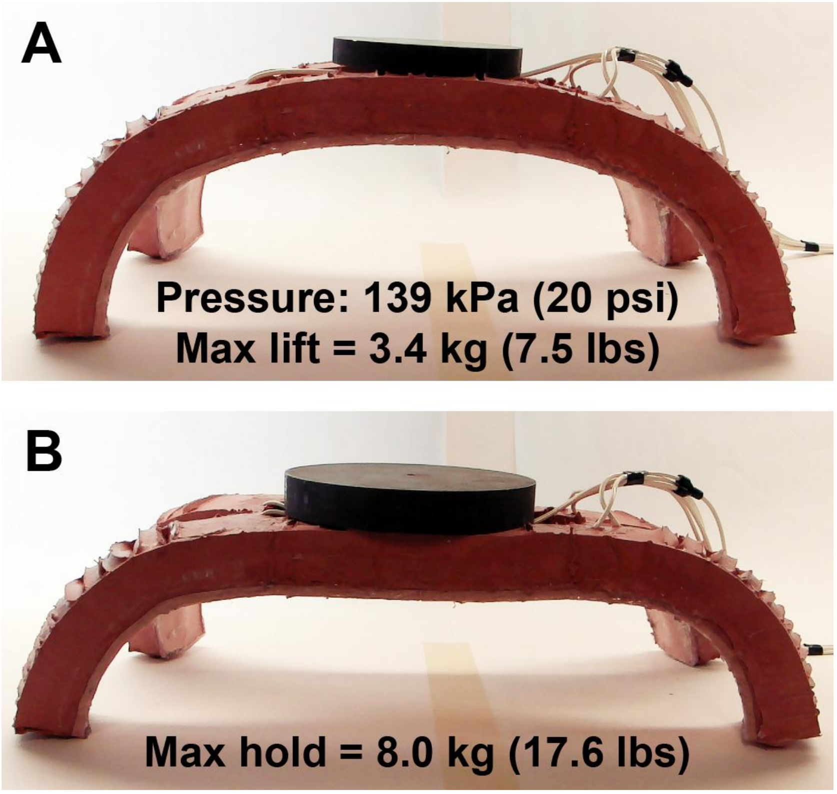
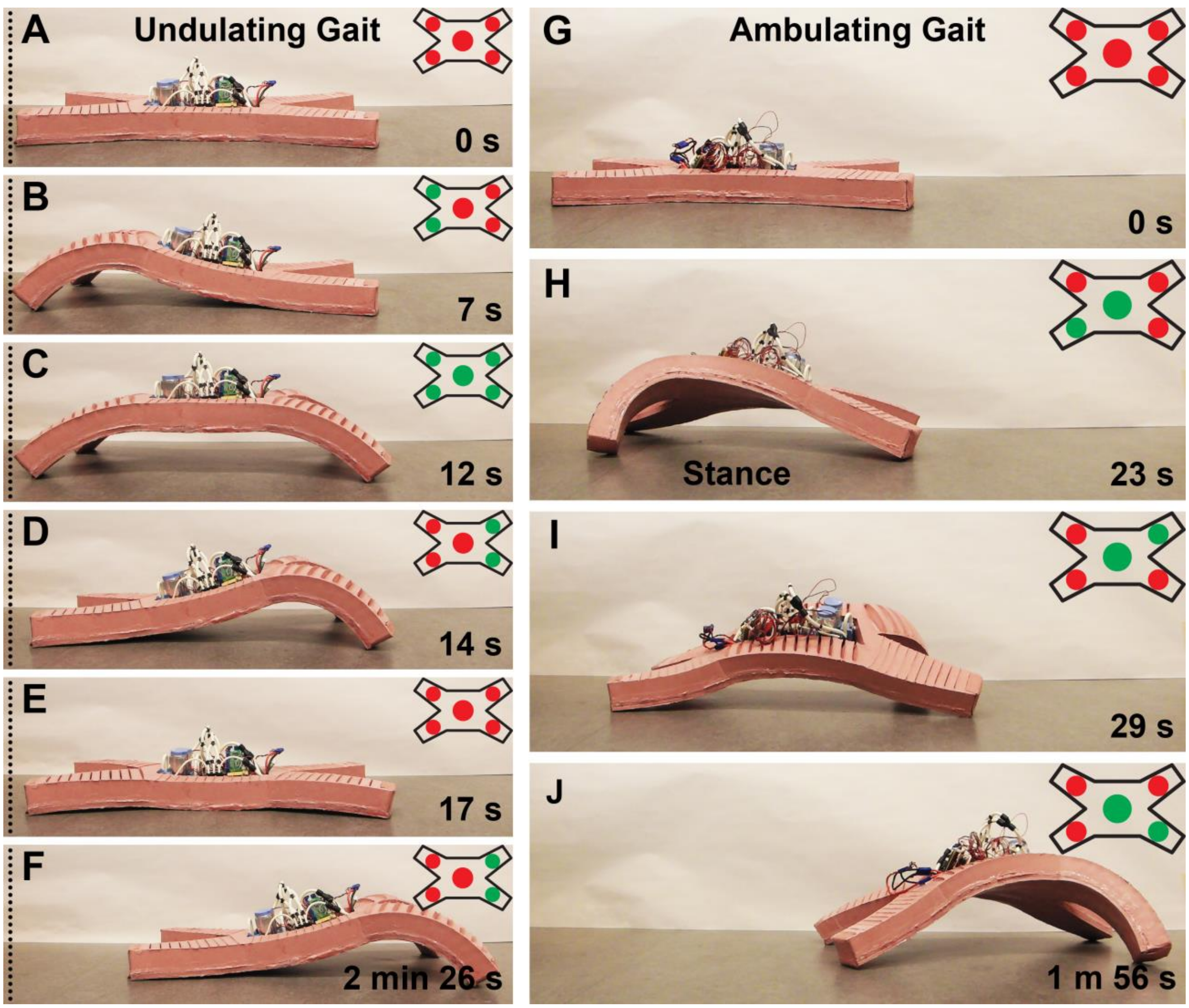


Figure S4. Frames from movies of the untethered soft robot executing undulating an ambulating gaits. **A-F** Undulating gait: The pneumatic channels are inflated sequentially from the rear of the robot toward the front, resulting in forward motion. Dotted lines mark the starting position for reference. **G-J** Ambulating gait: Starting from rest (**G),** a rear leg is actuated (**H**), the opposite front leg is then actuated to shift the weight forward (**I**). This sequence is repeated on alternating sides, resulting in a straight ambulatory gait (**J**). Green dots on the figures in the upper-right corner of each frame indicate which PNs are currently actuated (pressurized), red dots indicate unactuated PNs. The time elapsed since the start of the gait is indicated on each frame.



Video S1. Operation in extreme conditions**.** In this video we demonstrate the operation of our robot in four cases of extreme conditions: In snow, in fire, in water, and subjected to extreme crushing force. In all cases except in fire, the robot is operated untethered.

Video S2. Locomotion gaits. This video shows the soft robot locomoting untethered using two unique gaits: an undulating gait and an ambulating gait.

Video S3. Exploration mission. This video shows the untethered soft robot conducting a reconnaissance mission in a laboratory environment. Following a preprogrammed control sequence, the robot walks forward then turns left to walk into a small passageway. A forward facing camera (view overlaid in the lower-left corner of the screen) allows remote video recording.