Soft Robots

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Using Explosions to Power a Soft Robot**

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Soft robots have emerged as a new set of machines capable of manipulation[1–4] and locomotion.[5–8] Pneumatic expansion of a network of microchannels (pneu-nets) fabricated in organic elastomers, using low-pressure air (< 10 psi; 0.7 atm; 71 kPa), provides a simple method of achieving complex movements:[1,5] grasping and walking. Despite their advantages (simplicity of fabrication, actuation, and control; low cost; light weight), pneu-nets have the disadvantage that actuation using them is slow, in part because the viscosity of air limits the rate at which the gas can be delivered through tubes to fill and expand the microchannels. Herein, we demonstrate the rapid actuation of pneu-nets using a chemical reaction (the combustion of methane) to generate explosive bursts of pressure.

Although the combustion of hydrocarbons is ubiquitous in the actuation of hard systems (e.g., in the metal cylinder of a diesel or spark-ignited engine[9]), it has not been used to power soft machines. Herein, we demonstrate that explosive chemical reactions[10] producing pulses of high-temperature gas for pneu-net actuation provides simple, rapid, co-located power generation, and motion in soft robots. In particular, we used the explosive combustion of hydrocarbons triggered by an electrical spark to cause a soft robot to "jump" (a gait previously only demonstrated for hard systems[11–16]).

We fabricated a tripedal robot (Figure 1; Supporting Information, Figure S4) using soft lithography.[1] This robot incorporated a passive valving system (Figure 1 a, inset) that allowed us to 1) pressurize the pneu-nets easily, 2) exhaust the product gases automatically (without external control), and 3) actuate the same pneu-net repeatedly. By actuating all three legs simultaneously, we caused the robot to jump more

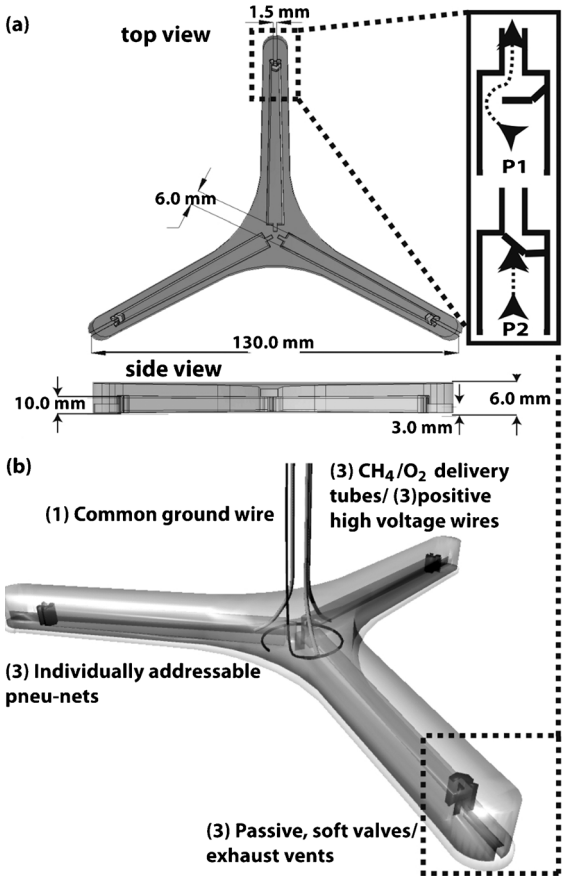

Figure 1. a) Scheme, including dimensions, of a tripedal soft robot. Inset: Soft valves allow low pressure (P1) gas to flow out of the exhaust vents in the pneu-net. High pressure (P2) closes the soft valve. b) Rendering of the robot with electrical inputs for spark ignition to actuate the pneu-nets explosively. We fed one wire (a common ground) through each of the pneu-nets, and a separate wire into each channel (a positive terminal for high voltage, three total) to allow independent, timed actuation of each leg. Each of the three high-voltage wires was sheathed in tubing that fed premixed methane and oxygen gas into the pneu-nets.

than 30 times its height in less than 0.2 s, at a maximum vertical velocity of approximately 3.6 m s^{-1}.

Our choice of explosive chemical reactions for actuation was based on several factors, one being their high volumetric energy density (in units of MJ L^{-1}). The energy density of a compressed gas, which we previously used to power soft robots, is approximately 0.1 MJ L^{-1} at 2900 psi from the potential for mechanical work, w, done by the change in pressure (ΔP), and volume (ΔV) when decompressed to atmospheric pressure; combustible gases, like CH_4, can also

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be burned to release heat, q, resulting in an energy density of $w+q \approx 8.0\ \mathrm{MJ\,L^{-1}}$ (see the Supporting Information). We used a stoichiometric mixture of methane and oxygen (1 mole CH_4:2 moles O_2) to power the jumps. This stoichiometry minimized the formation of soot, and prevented the contamination of the channels and the clogging of the valves by carbon deposits. We used an electrical spark to ignite the mixture inside the chambers because spark gaps are 1) easily incorporated into soft robots, 2) controlled in their timing with millisecond precision, and 3) faster than other means of ignition (e.g., resistive heating).

We chose pure oxygen instead of air to maximize the energy density of the mixture; air contains only approximately 21 wt % O_2. Methane was chosen as the fuel because it is 1) readily available, 2) a gas over all the temperatures useful for soft robots and easily pumped through tubing and pneu-nets, 3) easily controlled to ignite an explosion (i.e., rapid burning) rather than a detonation (i.e., a shock wave),[10,17] 4) sufficiently exothermic in combustion that it releases enough energy ($890\ \mathrm{kJ\,mol^{-1}}$; Equation (1)[18]) for

$$CH_{4(g)} + 2\,O_{2(g)} \rightarrow CO_{2(g)} + 2\,H_2O_{(g)} + 890\ \mathrm{kJ\,mol^{-1}} \quad (1)$$

actuation, but not enough to damage the channel or passive valve, and 4) converted by combustion into products (CO_2 (g) and H_2O (g)) that allow rapid depressurization of the actuator at the end of each cycle through a soft microvalve.

We fabricated the robot using soft lithography (see the Supporting Information).[1,5] Each leg of the tripedal robot was a hollow chamber with a stoichiometric mixture of CH_4 and O_2 entering from one side, and gases exiting through a valved opening at the other. At the gas-input side of each pneu-net, we placed computer-controlled electrodes that triggered a spark (Supporting Information).

The high temperatures of explosive reactions ($T > 2500$ K in air)[17,19,20] seem incompatible with the low service temperature of silicone elastomers (most degrade at $T < 600$ K).[21] To a first approximation, the temperature within a pneu-net during the explosion can be estimated using Equation (2),[20]

$$\Delta T = \frac{Q}{n_{CO_2} C_v^{CO_2} + n_{H_2O} C_v^{H_2O}} \quad (2)$$

where $C_v^{CO_2} = 28.6\ \mathrm{J\,mol^{-1}\,K^{-1}}$ and $C_v^{H_2O} = 74.5\ \mathrm{J\,mol^{-1}\,K^{-1}}$, $n_{CO_2} = 20\ \mu\mathrm{mol}$ and $n_{H_2O} = 40\ \mu\mathrm{mol}$, and $Q \approx 18$ J based on our gas-flow rates and channel dimensions; a more detailed analysis (in the Supporting Information) based on Equation (2) that includes second-order effects predicts a temperature of 3000 K (2800 °C) immediately after ignition. In our pneu-nets, a thin layer of silicone may decompose on exposure to high temperatures,[22] and form a surface layer of silica; this layer may insulate the surface from the radiant heat of the flame.[23]

The duration of the explosion is short. The temperature of the gas is quickly reduced as it expands and the pneu-net inflates. To try and capture the kinetics of the rapid combustion, we used a combination of high-speed infrared (IR) imaging (155 fps; T620; FLIR, Inc.) and bimetallic temperature probes in the interior of a pneu-net. We do not know how the IR intensity detected by the camera partitions between emissions from the hot gas, the surface, and the bulk polymer of the robot, but empirically, three milliseconds after ignition, we detected an IR temperature in excess of 500 °C (Figure 2 a,b). After ten milliseconds, the temperature measured by the IR camera fell below 300 °C (below the decomposition temperature of silicone; Figure 2 a–d). The IR imaging also established that we could actuate a single pneu-net independently, by adjusting the delays between sparks in them (Figure 2 e–h).

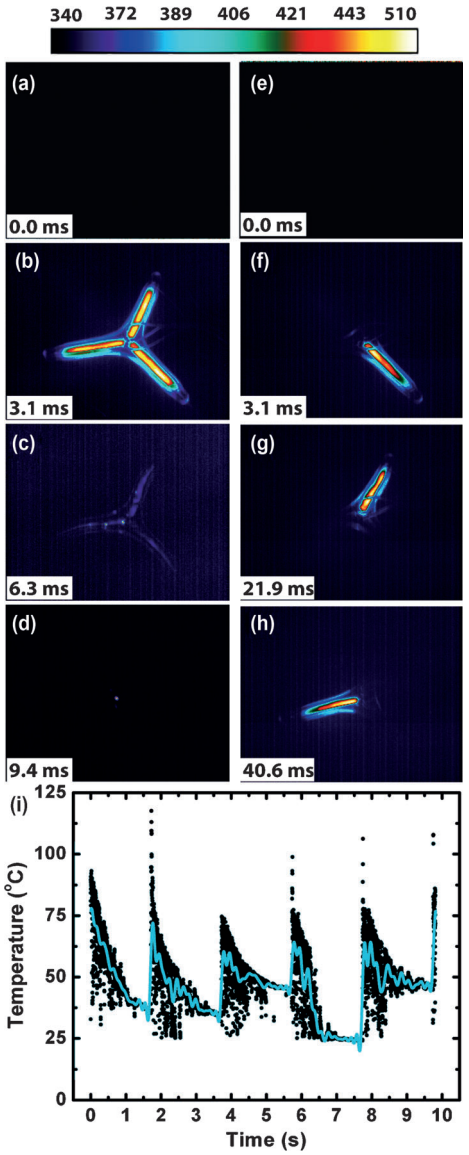

Figure 2. Infrared images of the top of the robot after (a–d) simultaneous ignition of combustion in all three channels and (e–h) separate actuation of the three pneu-nets with 15 ms delays between actuations. The channels have an IR signature below 510 °C for 6.3 ms; after 9.4 ms, the temperature of the robot is below 340 °C. The colorimetric temperature scale is shown in °C. i) The temperature measured within the pneu-net via thermocouple. Black dots are the raw data and turquoise lines are the "averaged" data (using a fast Fourier-transform smoothing algorithm in Origin graphing software).

To measure the temperature of the exhaust gases during a sequence of actuations (one actuation every two seconds; Figure 2i), we used a thermocouple (Supporting Information; Omega Instruments) placed inside the pneu-net. Because the response of the thermocouple is relatively slow, the measurements are averages over tens of milliseconds, and report the temperature of the exhaust gases (which do not exceed peak temperatures of approximately 125 °C, and cool to less than 50 °C prior to subsequent explosions). In principle, the stability of the CH_4/O_2 mixture in the absence of initiating events, and the small increase in temperature in the pneu-nets (approximately 25 °C above room temperature; Supporting Information) after the flame is extinguished, makes these systems safe to handle (Video S1). *We emphasize, nonetheless, that a mixture of CH_4/O_2 is highly dangerous, and should only be handled by experienced personnel.*

Using isothermal nanocalorimetry, we measured the heat evolution during actuation with 1) compressed air and 2) combustion of a mixture of CH_4/O_2 (Figure 3; Figure S2;[24] TA Instruments TAM-III; Supporting Information). From the resulting heat measurements and actuation times for compressed air (approximately 1 s)[5] and explosions (approximately 10 ms; Figure 2a–d), we estimate the power generated by these two actuation methods to be 3.3 mW and 35 W, respectively. The impulse (change in momentum over time) that results from the approximately 11 000-fold increase in power causes rapid actuation of the pneu-nets, and enables the soft robot to jump.

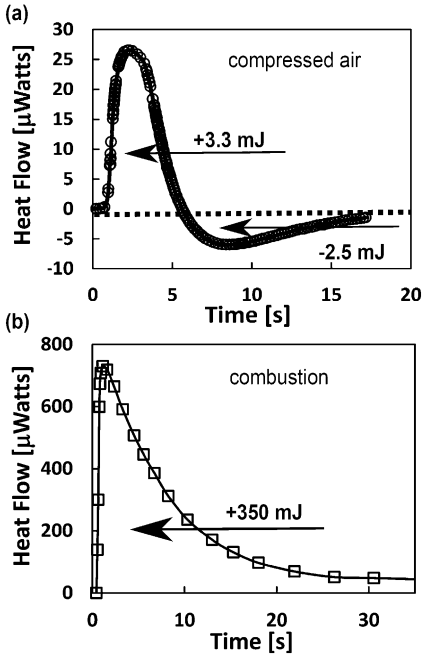

Figure 3. Calorimetric data for a) pneumatic actuation of a pneu-net with a 175 µL chamber volume. The heat produced (exothermic) while pressurizing the chamber by pumping air into the pneu-net (the area under the first curve) is 3.3 mJ; deactuating the pneu-net by sucking air out and depressurizing the chamber is endothermic and absorbs 2.5 mJ of heat (area above the second curve). b) Combustion in the same pneu-net evolves 350 mJ of heat (area under the heat flow versus time curve).

After the methane has burned in the pneu-net, it is necessary to remove the waste products to ensure an appropriate ratio of CH_4 and O_2 for the next actuation. To purge the waste CO_2 and H_2O vapor, we embedded exit channels into the ends of the legs of the tripod. To actuate a leg, we allowed fresh methane and oxygen to flow into the pneu-net and expel the exhaust gases.

The heat from the combustion reaction increases the pressure of gas in the pneu-net. To limit the expanding gas from leaking before the explosion was complete, we embedded a passive valve—a soft flap molded directly into the pneu-net—immediately before the exit channel (Figure 1a, inset). At low pressure—before, and approximately 10 ms after, an explosion—the soft valve was open and allowed continuous flow of fuel into the pneu-net, or of waste products out of it. At high pressure—during the explosions—the soft valve closed and caused the pressure to increase and actuate the pneu-net (Figure 4a; Video S2, see text in the Supporting Information for an estimate of pressure during the explosion). Approximately seven milliseconds after the spark ignited the CH_4/O_2, the pressure generated by the exploding gas caused the leg to inflate (Figure 4a), and then, approximately 50 ms after ignition, to extend about 5 mm; this extension, in turn, caused the actuator to bend downward (Figure 4b–e).

Despite the large pressures generated during the explosions, the pneu-nets (fabricated from a stiff silicone rubber, Young's modulus approximately 3.6 kPa; Supporting Information) withstood multiple (>30) explosive actuations before failure. These failures typically occurred from the charring of the gas input lines and, occasionally, from tearing of the elastomers at the interface between the actuation layer and the strain-limiting layer.

The toughness and resilience of these silicone elastomers was further evident when we actuated all three legs simultaneously. The tripedal robot contained the three simultaneous explosions and used the energy they generated to jump over 30 times its body height (that is, 30 cm) in under 0.2 s (Figure 5; Video S3). We used high-speed video to estimate the instantaneous velocity after actuation: the robot jumped 2.5 cm in 8.25 ms, with a resultant velocity of 3.6 $m s^{-1}$ (13 $km h^{-1}$). The 30 cm height was, in reality, limited by the height of the safety chamber we used to enclose the jumping robot; we estimate that the robot would actually have reached a height of 60 cm in a taller chamber, and without the weight of the attached tubing (Supporting Information).

The use of explosions for actuation is compatible with soft machines. Explosive power allowed a soft robot to jump 30 times its height with an initial speed of 3.6 $m s^{-1}$; a mobile robot powered by compressed air moved much more slowly (walking at approximately 0.03 $m s^{-1}$).[5] The silicone-based robot, whose body design we made no attempt to optimize, withstood the tensile forces and temperatures generated by igniting a mixture of methane and oxygen within its pneu-nets. The heat capacity of the robot (approximately 44 J/K; Supporting Information) was enough to absorb the heat generated from the rapidly burning gas (approximately 18 J).

Recently, the use of jumping in hard robotic systems (e.g., the "Sandflea" by Boston Dynamics) has been demonstrated as a way to navigate obstacles. We believe that soft robots

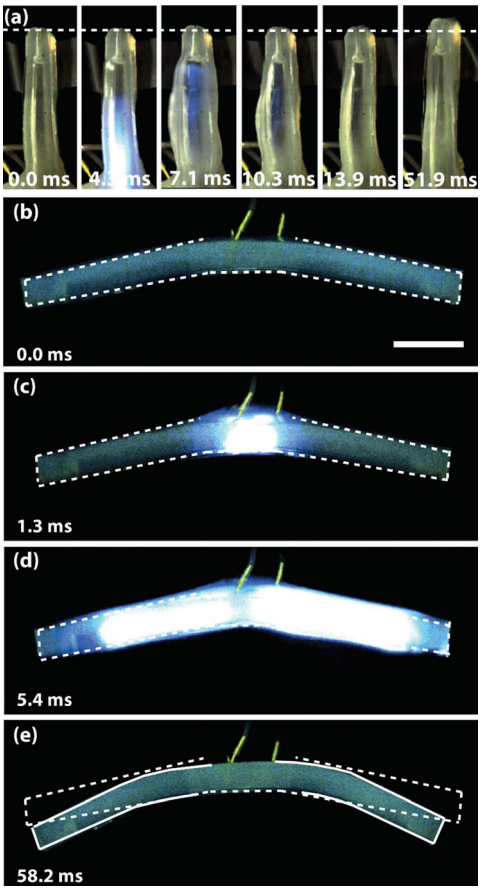

Figure 4. Optical micrographs of a pneu-net while being explosively actuated, acquired using a high-speed camera. a) Top view of a leg of the tripod. Left to right: An electrical arc (0.0 ms) triggers explosive combustion of methane with a visible flame that persists for 10.3 ms. At 7.1 ms, a soft valve prevents propagation of the flame and pressure wave during the explosion. After 50 ms, the stored elastic energy stretches the pneu-net. Side view of the tripod b) before and c) after ignition of methane oxidation. d) The flame front propagates to the end of the pneu-nets and e) the stored elastic energy is released as a downward motion. The dashed line shows the angle of deflection of the robot's feet, at rest. The solid line shows the angle of deflection of the robot under explosive actuation—the rest angle of deflection (dashed line) is overlaid. Scale bar = 2 cm.

powered by explosive actuation, with future improvements in design and control,[25] could be autonomous and able to jump to navigate obstacles in search and rescue missions; additionally, the cost of these robots (approximately $100; see Supporting Information for estimate) would be sufficiently low that they could be considered disposable, with insignificant loss if they were destroyed during use.

The soft robot described in this work can be further developed to convert chemical potential into useful mechanical work (see Supporting Information for the efficiency calculation). By tailoring the timing in the sparks, it will be possible to increase the jumping height, improve energy efficiency, and direct the jump of the robot. Liquid butane (LB) and other liquid fuels (e.g., gasoline) have even greater volumetric energy densities than gaseous methane, and will be usable as fuels with improved design.

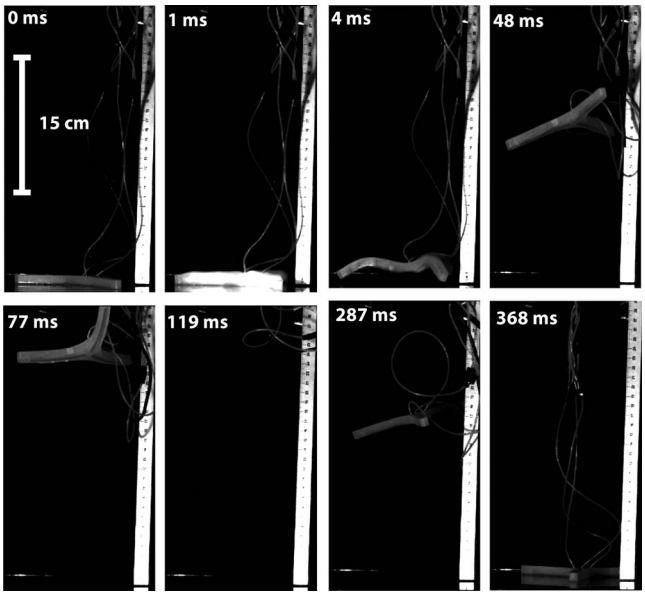

Figure 5. Time sequence of a jumping robot. Ignition of all three channels begins at 1 ms. The robot leaps from the ground at 4 ms and exceeds 30 cm height after 119 ms. The robot returns to the ground at 368 ms. Tubing and electrical wire is visible in all frames. The scale bar is 15 cm.

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