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An Untethered Jumping Soft Robot*

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***Abstract*— Locomoting soft robots typically walk or crawl slowly relative to their rigid counterparts. In order to execute agile behaviors such as jumping, rapid actuation modes are required. Here we present an untethered soft-bodied robot that uses a combination of pneumatic and explosive actuators to execute directional jumping maneuvers. This robot can autonomously jump up to 0.6 meters laterally with an apex of up to 0.6 meters (7.5 times it's body height) and can achieve targeted jumping onto an object. The robot is able to execute these directed jumps while carrying the required fuel, pneumatics, control electronics, and battery. We also present a thermodynamic model for the combustion of butane used to power jumping, and calculate the theoretical maximum work output for the design. From experimental results, we find the mechanical efficiency of this prototype to be 0.8%.**

I. INTRODUCTION

Recently, new fabrication and control approaches have led to the development of a class of *soft robots*, mostly inspired by invertebrates such as worms or cephalopods, with few rigid internal elements [1], [2], [3], [4], [5]. We have previously developed a pneumatically actuated soft robot that walks with a quadrupedal gait [6], and recently, a quadrupedal walking robot that is sufficiently large and strong to carry all of the components required for untethered operation [7]. However, a major challenge for these pneumatic soft robots (as for many invertebrates) is rapid terrestrial locomotion (our untethered quadruped, for example, had a max speed of $\sim$18.0 m hr^{-1}).

A common strategy in nature for traversing rough terrain is jumping. While examples of jumping in animals without rigid internal or external skeletons are rare, some do exist such as the fruit-fly larva Ceratitis capitata [8]. Our goal is to develop a soft robotic system capable of such rapid, agile motions.

A number of mechanisms have been proposed to achieve jumping maneuvers in robots with rigid skeletons. Linear springs are one of the most obvious options. Some robots transfer energy to spring-loaded mechanisms (usually a four or six bar linkage) which are then released when a jump is desired [9], [10], [11], [12]. Other robots will cause propulsion by directly impacting the ground with a linear spring mechanism [13].

Torsion springs and bending springs are perhaps the most common options for achieving jumps. In a manner similar to linear springs, torsional springs can be used in a linkage mechanism to store energy which is released suddenly to initiate a jump [14], [15], [16]. Using this strategy can result in massive power amplification, allowing for very impressive

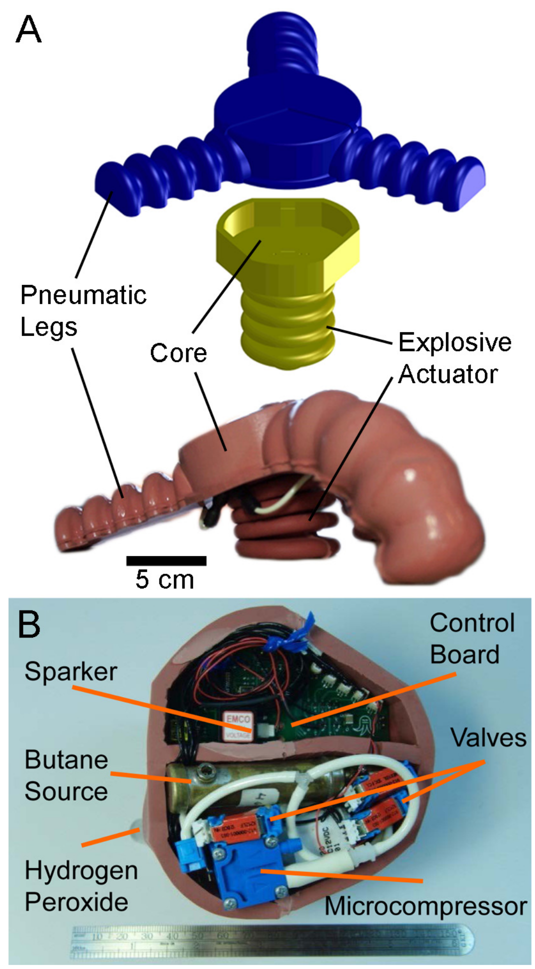

Fig. 1. Soft explosive jumper design. A) CAD model (top) and image (bottom) of the soft explosive jumper with main components labeled. B) Top view of core section with electrical, pneumatic, and chemical components labeled.

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jumps [17]. Other systems use a spherical cage surrounding the main body of the robot to act as a spring [18], [19], [20]. Still others use bending springs as a catapulting mechanism [21], or by taking advantage of snap-through buckling [22].

Less common modes of actuating jumping include pneumatics systems [23], [24], [25], [26], elastomers [27], and voice coils [28].

The use of chemical fuels for jumping robots is an option that has recently demonstrated promise. In a project taken over from Sandia National Laboratory, Boston Dynamics has created the Sand Flea, which uses disposable fuel cartridges, and can currently jump higher than any other robot [29]. However, this robot is composed of rigid components which may complicate landings and pose a hazard to humans with whom it interacts.

We have previously used combustion of methane to actuate soft, pneumatic networks (Pneu-Nets) rapidly and have demonstrated the ability of this type of actuation to produce bursts of power sufficient to cause soft mechanisms to jump [30]. However, tethers were used to deliver the combustion products and electrical ignition from stationary equipment. This prior work relied on a rapid bending motion in Pneu-Nets to achieve jumping; however, the rapid expansion of gas was very fast ($<$ 10 milliseconds) and the dominant effect of the combustion may have been due to outward expansion of the actuators as opposed to bending. The result was an excellent vertical leap (>40 cm for a robot 1 cm tall), but limited success in steering and lateral jumping. Nonetheless, this work demonstrated that the use of combustion to power soft robots has the potential to allow untethered operation for longer periods of time than would compressed air. The energy obtained by combustion of butane is 28 MJ/L or 49 MJ/kg; by comparison, the energy density of compressed air at 300 bar is 0.2 MJ/L or 0.5 MJ/kg.

Three advances are necessary for a broader use of combustion actuation in soft robots: (i) system design with onboard fuel storage for untethered actuation with combustion, (ii) improved directional control over jumping, and (iii) allowing more frequent and lower energy actuations for sequential jumps and non-jumping gaits (e.g., walking and running). In this paper we address issues (i) and (ii) (i.e. untethered actuation and controlling the direction of jumping). We present an untethered robot that uses a combination of pneumatic and explosive actuators to move in a jumping gait (Fig. 1). This robot can autonomously jump 0.6 meters laterally with an apex of 0.6 meters. We also demonstrate targeted jumping onto an object.

The next section discusses our proposed design in detail. An analysis of the energetics of this jumping approach is provided in Section III. The following section (Section IV) presents experimental results obtained with our soft jumping robot and discussions of our findings. Conclusions and suggestions for future work are presented in Section V.

II. Design and Fabrication

Our soft robot uses a combination of pneumatic and explosive actuators for locomotion. This mobile robot has three pneumatic actuators arranged at 120° relative to a central axis, and one explosively actuated piston in the center (Fig. 1). The pneumatic actuators position the center of mass of the robot to control the direction of jumps which are initiated by the explosive actuator (Fig. 2g-i). A core section houses the control components, fuel, and battery. The robot is approximately 8 cm in height with a 15 cm radius.

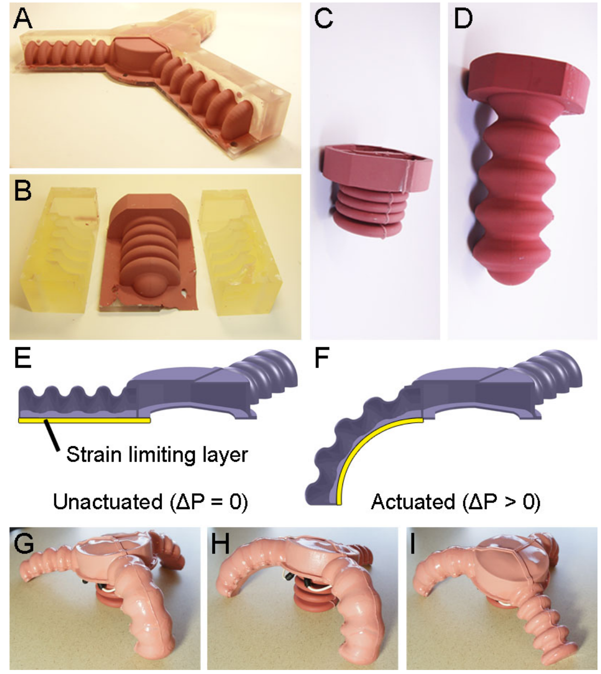

Fig. 2. Fabrication and pneumatic actuation of the soft explosive jumper. A) Two-part mold being disassembled to reveal the pneumatic actuators of the jumping soft robot. B) Demolding the explosive actuator; this figure represents just one half of the piston. The second half is identical and the two parts are "glued" together to form C) the soft piston. D) When actuated, the piston extends linearly. E-F) Cross-sections of the body and one of the pneumatic legs of the robot demonstrating the principle of operation of the pneumatic legs. A strain limiting layer on the bottom of the leg causes the leg to bend downward when inflated. G) Onboard microcompressor and valves control the inflation of the three pneumatic legs to position the center of mass of the robot to the left, H) back-right, or I) front-right prior to an explosive jump.

The main actuator which powers the jumps of the robot is a linear actuator with a bellows geometry that extends when pressurized (Figure 2c,d); we power this actuator using the explosive combustion of butane. When actuated, this piston expands rapidly (in ∼30 ms) towards the ground, imparting an impulse on the body of the robot and causing it to leap into the air.

In a previous (unpublished) prototype, we investigated adding an explosive segment to the end of each of three legs of a soft robot (Fig. 3). However, due to the rapid timescale of explosive actuation, we were unable to consistently control the direction of jumps by timing the actuation of the three explosive segments.

Due to the larger volume of the explosive actuator than in prior prototypes (∼20 mL vs. ∼2 mL, [30]), we chose a tougher silicone rubber (M4601, Wacker Chemicals; ∼300 MJ/cm^3 vs. ∼75 MJ/cm^3; see [7] for a comparison of these materials for use in untethered soft robotics) to withstand

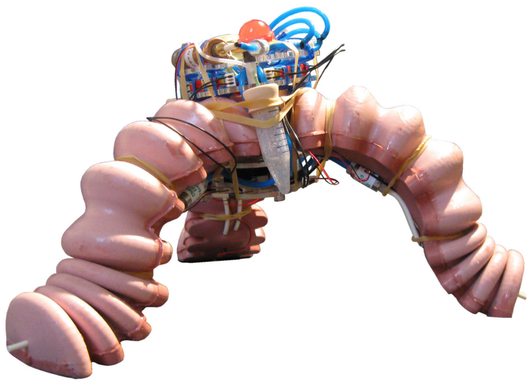

Fig. 3. Previous untethered explosive jumping soft robot prototype. Our initial design had an explosive actuator segment at the end of each of three legs. This design achieved jumps of up to 0.2 m in height but could not jump laterally.

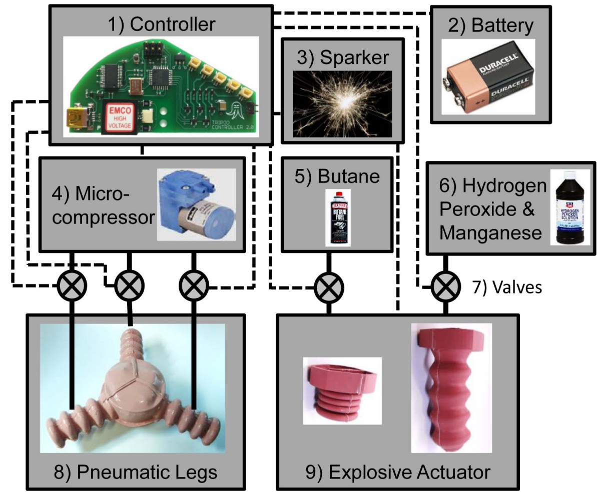

Fig. 4. System schematic of soft robot components. A custom control board (1), powered by a standard 9 volt battery (2), controls the sparker (3), microcompressor (4), and valves (7). The microcompressor inflates the pneumatic legs (8) to direct jumping. Butane (5) and hydrogen peroxide (6) sources provide the combustion reactants to the explosive actuator (9), which are ignited by the sparker to cause the robot to jump.

the power and sudden increase in pressure of the combustion event.

An array of three individually addressable pneumatic actuators allowed us to shift the position of the center of mass of the robot over this explosive actuator (Figure 2g-i). Similar to our previous Pneu-Net design [6], these bending actuators consist of a pneumatic channel attached to a strain-limiting layer which causes the channel to bend when inflated. For the strain-limiting layer we impregnated a polyaramid fabric with the same elastomer used for the body of the robot.

We used a larger overall body architecture than in prior work ($\sim$15 cm vs. $\sim$6 cm radius, [30]) to support the components (batteries, microcontroller, fuel and oxidizer, and valves) necessary for untethered operation of the jumping robot. The total mass of the robot was 510 g.

To power the untethered robot, we used liquid butane as the fuel source due to its high energy density in liquid form (28 MJ/L), and its commercial availability in portable packages (e.g. in cigarette lighter fuel sources). A butane source from a portable soldering torch (Master Appliance MT-476) provided onboard fuel storage. To facilitate combustion, the butane was mixed with oxygen which was derived from the manganese catalyzed decomposition of hydrogen peroxide (5 mL 10% H_2O_2). Prior to a jump, the manganese catalyst was added to hydrogen peroxide to produce pressurized oxygen in a sample vial attached to the body of the robot.

A schematic of the system components and interfaces can be found in Fig. 4. Pneumatic actuation was provided by a micro diaphragm pump (CTS Series, Parker Systems), and controlled with three three-way solenoid valves (X-Valve, Parker Hannifin Corporation). Two more of these valves controlled the delivery of pressurized butane and oxygen. We built a custom board to control the microcompressor, valves, and provide electrical sparks for ignition of combustion using a high voltage source (Q Series, EMCO High Voltage Corporation) connected to a sparker lead (see Fig. 5 for a simplified schematic of this board). An Arduino bootloader was installed on the custom control board to simplify the programming of control sequences. All components were powered by a standard 9V battery.

The fabrication of the jumping soft robot was based on the soft-lithography approach used previously to fabricate soft robots [31]. However, unlike previous approaches, the complex three-dimensional geometry of this jumping soft robot design required pairs of two-part molds for each component (Fig. 2a,b). Thus, we printed inner and outer molds on a high precision 3D printer (Connex 500, Stratasys, Ltd.), into which we poured the silicone elastomer body material to create halves of the pneumatic and explosive actuators. We then bonded these half-components together with an uncured layer of the same silicone elastomer.

III. Model

In this section we present a thermodynamic model of a combustion-powered jump of our soft robot. This model is based on the Otto cycle (the idealized thermodynamic cycle used to model internal combustion engines). Although the ideal Otto cycle assumes a rigid volume (as is found in an internal combustion engine), it serves as a first approximation for a soft system. The timescale of the explosive phase is assumed to be sufficiently short that elastomer strain can be neglected.

The Otto cycle consists of a number of processes. From ignition (1) to the end of combustion (2), there is a phase of constant volume heat addition. After all the heat from combustion has been absorbed by the working fluid, the cycle moves into isentropic expansion. The volume expands until limited by the geometry of the system (3), and then there is a phase of constant volume heat rejection, followed by isentropic contraction back to the original state (Fig. 6).

Assuming atmospheric conditions (temperature and pressure) at ignition, we calculated the temperature at the end of combustion (T_2) using the heat of combustion of butane ($\Delta H^\circ_{C,butane}$), the specific heat of oxygen ($c_{v,oxygen}$), and

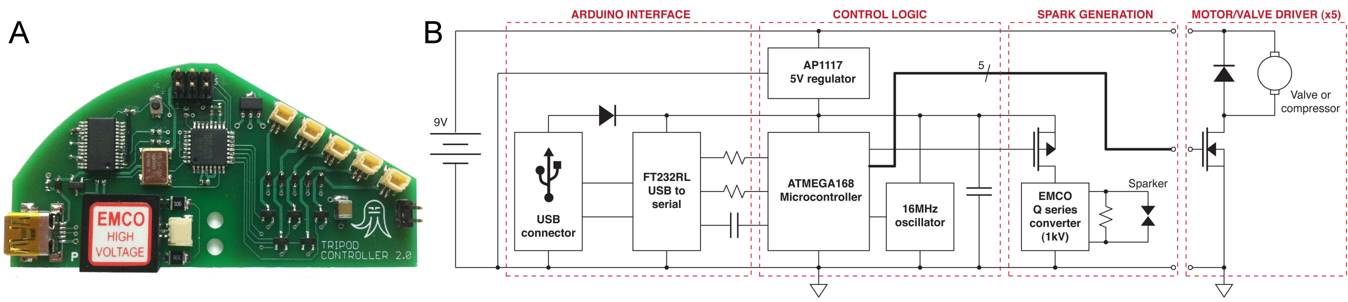

Fig. 5. Simplified schematic of the custom control board used to control the microcompressor, valves, and high voltage sparker of the jumping soft robot.

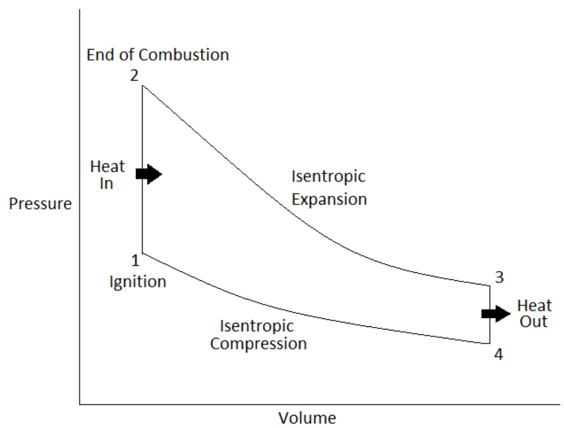

Fig. 6. A depiction of the idealized Otto Cycle. After ignition (1), there is a phase of constant volume heat addition, until the end of combustion (2). Isentropic expansion occurs until the final volume is reached (3), and then there is a phase of constant volume heat rejection, until isentropic compression begins (4).

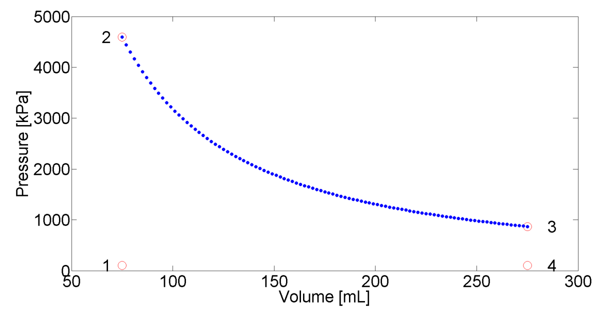

Fig. 7. The P-V diagram for the cycle calculated by our model. The points corresponding to points (1)-(4) on the idealized Otto Cycle are marked by red circles.

the masses of butane (m_{butane}) and oxygen (m_{oxygen}):

$$T_2 - T_1 = \frac{\Delta H^{\circ}_{C,butane}\, m_{butane}}{c_{v,oxygen}\, m_{oxygen}} \tag{1}$$

However, one should note that stoichiometric considerations necessitate a fixed ratio of oxygen to butane, so the amount of oxygen is in fact a function of the amount of butane (both of which are constrained by the geometry of the robot):

$$m_{oxygen} = m_{butane} \frac{MM_{oxygen}}{MM_{butane}} \gamma \tag{2}$$

Here, MM_{oxygen} and MM_{butane} are the molar masses of oxygen and butane (respectively), and γ is the stoichiometric ratio of oxygen to butane (in our case γ = 6.5). Thus, the temperature at the end of combustion is not a function of the amount of butane used for a jump; once the geometry of the robot is defined, an ideal amount of fuel is specified (based on the initial volume and the ideal fuel ratio), which determines the jump height. This relationship should therefore be taken into consideration at design time to identify the ideal ratio of initial to final explosive actuator volume to achieve a jump of a desired height. However, since the overall mass of the system is also a function of this volume ratio, it may be necessary to solve the design problem iteratively.

Knowing the temperature at the end of combustion, the ideal gas law is used (in conjunction with the fact that the volume has not changed) to find the pressure P_2:

$$P_2 = P_1 \frac{T_2}{T_1} \tag{3}$$

The isentropic relation (Eq. 4)–where V_2/V_3 is the ratio of the volumes before and after isentropic expansion, and k is the ratio of specific heats–determines the curve from the end of combustion to the final volume (Fig. 7).

$$\frac{P_3}{P_2} = \left(\frac{V_2}{V_3}\right)^k \tag{4}$$

Finally, the cycle ends with the system transferring any remaining heat from combustion to the environment at atmospheric pressure.

For the geometry of this particular robot, with a mass of 510 g, an initial volume of the explosive actuator of 75 mL, and a final (expanded) volume of 275 mL, the model predicts that 355 J of work will be generated (given by the area within the process curve defined by this cycle). The theoretical ideal amount of butane for this system is 26 mg. Based on the heat of combustion of butane (49 MJ/kg), the heat output from this amount of fuel is 1274 J. Thus, the Otto cycle predicts a thermodynamic efficiency of about 28%. If the robot were 100% mechanically efficient, this amount of work would result in a jump of about 70 meters.

IV. Results and Discussion

In experiments, we tested the ability of the jumping soft robot to jump in a predetermined direction, and to execute

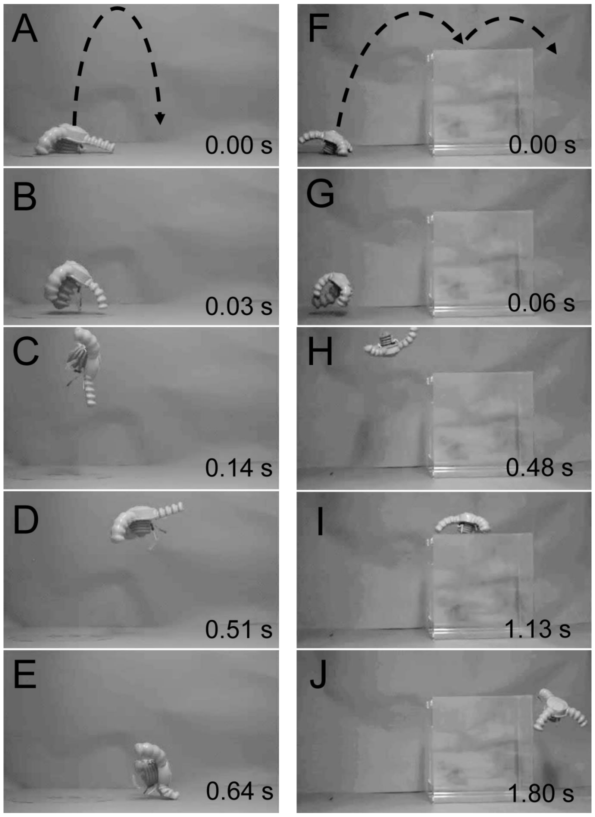

Fig. 8. Jumping experiments. A-E) Directional jump: the robot jumps a height of $\sim$0.6 m, and $\sim$0.3 m laterally in the direction of the unactuated pneumatic leg (to the right). The jump is completed in 0.7 seconds. The dashed line in A is a trace of the center of mass of the robot during its jump. F-J) Jumping onto an object (a clear acrylic box). A targeted jump allows the robot to jump onto an object. Each image is a frame from a video of one of the two jump experiments (respectively) taken at 500 frames per second. The time since the initiation of each jump is indicated in the lower-right corner of each frame.

a targeted jump onto an object. Fig. 8a-e shows the robot performing a directional jump to the right. In this case, we caused the robot to jump $\sim$0.3 meters laterally with the jump reaching an apex of $\sim$0.6 meters (see Movie S1). The robot jumped this distance in 0.7 seconds. We actuated the soft piston with $\sim$5 mL (12 mg) of butane and $\sim$30 mL (43 mg) oxygen gas to jump $\sim$0.6 meters vertically (Fig. 8).

The custom control board activated the microcompressor and solenoid valves to inflate the pneumatic legs, setting the pose of the jump (see Fig. 2g-i). The legs were designed to bend from horizontal to 90° when fully inflated. As shown in Movie S1, it takes $\sim$15 s to fully inflate the two legs required to set a pose.

The stoichiometry of butane combustion (Eq. 5) requires an oxidative environment with a precise ratio of butane and oxygen for ignition. In order to facilitate ignition at room temperature and atmospheric pressure, we provided an enriched oxygen environment. We generated oxygen onboard from the catalytic decomposition of H_2O_2. A butane source provided the fuel. To dispense 5 mL of butane, the associated solenoid valve was opened for 5 ms, while the oxygen valve was opened for 10 s to dispense 30 mL of oxygen gas, yielding a volumetric ratio of 6. Based on Eq. 5, the ideal stoichiometric ratio of pure oxygen to butane is 6.5, which translates to an ideal volumetric ratio of $\sim$6.2. A spark then ignited the mixture to cause the robot to jump.

$$2C_4H_{10(g)} + 13O_{2(g)} \rightarrow 8CO_{2(g)} + 10H_2O_{(l)} + 2.9MJ/mol \tag{5}$$

The amount of butane used for this jump (12 mg) was less than the ideal amount predicted by the theoretical model (26 mg), although greater than the ideal amount if ignition were to occur in pure air (7.5 mg). This intermediate value reflects the fact that, although the model assumes a perfectly oxygenated ignition environment, in reality it was a mixture of air and oxygen. The energy output from 12 mg of butane is $\sim$588 J and the potential energy gain from moving a 510 g object to a position 0.6 meters higher is $\sim$3 J. Therefore the total efficiency of this jump is $\sim$0.5%. However, our thermodynamic model predicts a maximum work output of 355 J; thus, we can characterize the mechanical efficiency of our prototype system to be $\sim$0.8%.

In another experiment, the robot successfully jumped onto a target object (an acrylic box) with a height of 0.5 m (Fig. 8f-j). In this experiment, the robot jumped $\sim$0.6 m in height and $\sim$0.6 m laterally. However, due to its momentum, and without grippers or another approach for adhering to target objects, our robot was not able to come to rest on top of a target object. For this experiment, the electrical spark for ignition was provided from an off-board source due to failure of the on-board sparking mechanism. This electrical connection disconnected itself at the start of the jump (leaving behind a connector visible in Movie S1).

Our new design and choice of materials allowed us to pressurize the internal channels to $\sim$138 kPa (20 psi), five times that of our prior Pneu-Nets; accordingly, the robot was able to carry the larger load of the onboard components required for untethered actuation. Additionally, the chosen body material and fabrication approach for the explosive actuator (see Section II) withstood many (>30) explosive tests without failure. While the high temperatures of explosive reactions (T>2500 K in air) may seem incompatible with the low service temperature of silicone elastomers (<600 K), consistent with previous tethered experiments [30], we observed no damage in our silicone combustion chamber.

The use of independent explosive and pneumatic actuators for powering and controlling jumping was a successful approach to achieving such fast maneuvers in a soft robot. As with many robotic designs, a decoupling of the power and control actuators simplified the design and control of our soft robot.

While practical challenges prevented us from achieving multiple successive jumps (see the following section for details), fuel was not a limiting factor. The robot was able to carry up to 5 g of butane, enough for >400 actuations at 12 mg each. Similarly, the hydrogen peroxide vial could hold 10 mL, sufficient to produce enough oxygen for 80 actuations which each use 43 mg of oxygen.

V. Conclusions

We have presented an untethered soft robot that uses combustion to achieve directional jumping maneuvers. The ability to leap over obstacles would allow soft robots to traverse uneven terrain, greatly expanding their utility for applications such as search and rescue. In addition, rapid actuation with combustion may improve the overall speed and efficiency of future soft robot designs.

One of the challenges with the design presented here is that there are many points of failure for the integrated electrical, chemical, pneumatic and mechanical systems. Due to the absence of the rigid skeleton found in most robots, and also the large forces experienced during jumping, the reliability of interfaces between the various components is of critical importance. We attempted to protect these components inside the soft body of the robot, but we nonetheless experienced many failures at electrical connectors or barbed tube fittings that were difficult to identify and fix without disassembling the robot.

Another key challenge with our design was achieving successive jumps. Our robot did not have facilities to autonomously reset its orientation and the position of its explosive actuator after a jump. Thus, if the robot landed on its back, or with the explosive actuator extended to one side, it would not be able to position itself for another jump. Additionally, the robot did not have an additional valve to exhaust the combustion products after a jump. We hope to address these challenges in future work.

A third challenge motivated by our results as discussed in Section IV is that of gripping or adhering to target surfaces. Future work in jumping soft robots could address all three of these challenges.

Finally, further modeling is required to account for deformation of the soft body during explosive actuation, and to predict the dynamics of the robot while executing a jump.

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