***Volumetric Energy Density of Compressed Air and Compressed Methane.*** Volumetric energy density is a combination of the potential for *mechanical* work, *w*, done by the change in pressure ($\Delta$P), and volume ($\Delta$V), and the *chemical* heat, *q*, released from burning the gas. For example, compressed air at 2,900 psi (~197 atm) has an energy density of 0.1 MJ/L calculated from P$\Delta$V and compressed methane (at 2,900 psi) has an energy density of 8.0 MJ/L calculated from the combination of P$\Delta$V and heat of combustion (Eq. 1).

***Estimate of Pressure Immediately After Ignition.*** Using the unpressurized channel volume of 1.0 mL, and our theoretically estimated temperature immediately after ignition of 2,800 $^{o}$C, we calculated the maximum pressure, using the ideal gas law, to be ~1 MPa (~140 psi). Though this value is an overestimate (it does not take into account the channel volume expansion and the gas cooling, a complex calculation that is beyond the scope of this paper), we use it to illustrate the quick impulse of high pressure to use a passive valving system to control the flow of gas out of the channel after combustion and cooling.

***Fabrication of the Robot.*** The elastomer we used for the actuation layer was a stiff silicone rubber (Dragon Skin 10, DS-10; Smooth-on, Inc.). This elastomer has a greater Young's modulus than our previous choice for pneumatic actuation (Ecoflex 00-30; Smooth-on, Inc.); pneu-nets composed of DS-10 could withstand the large forces generated within the channels during the explosion better than Ecoflex; in addition, DS-10 has a high resilience, which allowed the pneu-nets to release stored elastic energy rapidly for propulsion (Fig. S1). To seal the pneu-net, we bonded a compliant and relatively inextensible silicone rubber (Sylgard 184; Dow

Corning) to the actuation layer using a thin layer of uncured silicone (Sylgard 184) and then allowed the silicone to cure at room temperature over 12 hours.

We mixed the methane and oxygen gases off-board the robot and injected the mixture, separately, into each leg, at a rate of 12 mL/min. In order to assure that we delivered a stoichiometric mixture of $CH_4$ and $O_2$, we used mass-flow controllers (100SCCM; MKS Instruments). We used capacitive discharge modules (CDIs), available from the hobby radio-controlled airplane industry (part# RCEXL; Paragon RC, Inc.), to generate the large potentials (~6.6 kV at 2 mm electrode separation, or ~33 kV/cm, 10 times the approximate breakdown voltage of these gases [1]) to produce the sparks to ignite the gas mixture (Fig. S3). We threaded a single ground wire through all three pneu-nets of the tripod and we threaded the positive electrodes–coaxially–through each of the (three) gas delivery tubes (Figure 1b). We used an Arduino control board to trigger the CDIs to generate the spark between the desired positive electrode(s) and the common ground wire.

***Temperature Change and Efficiency.*** We calculated the temperature change in the explosion of the methane/oxygen mixture ($\Delta$T) by first calculating the channel volume and therefore the number of moles of carbon dioxide ($n_{CO2}$) and water ($n_{O2}$) in that volume, as produced by explosion of the stoichiometric mixture of $CH_4$ and $O_2$, assuming standard temperature and pressure. The standard enthalpies of formation of the two products are reported in the literature as $C_v^{CO2}$ = 28.6 J/mol·K and $C_v^{O2}$ = 74.5 J/mol·K.

The energy generated by the robot in the system can be calculated using the method outlined in the MATLAB® script below. This calculation uses the mass of the robot (30 grams, excluding external tubing) and the final height of the jump to calculate the potential energy generated by the robot using standard Newtonian physics (P.E. = mgh). For accuracy the potential energy used in lifting the weight of the feed tubes to the robot is also included. An alternative approach would be to calculate the velocity, v, of the robot immediately after it leaves the surface and use this measure to estimate the kinetic energy (K.E. = $1/2mv^2$). We implemented this approach using high speed video analysis, and the resulting energies (P.E. = 0.13 J vs. K.E. = 0.20 J are within the right order of magnitude as a good check. The chemical energy developed in the combustion of 20 μmol of methane and 40 μmol of oxygen is ~18 J, as calculated using enthalpy of combustion of methane (from the standard enthalpies of formation of the products). We used this value to estimate the efficiency of the system; efficiency = (mechanical energy out / chemical energy in)*100%, which we evaluated as ~0.7%.

***Measurement of the Heat Evolution During Explosive Actuation Using Nanocalorimetry.*** The nanocalorimeter we used (1 nanoWatt sensitivity) measures the heat flow in units of (μJ/s) as a function of time, and the integral of this curve is the heat ($q$) evolved or absorbed [2]. Due to the volume constraint of the cylindrical cell of the calorimeter (the cylinder was 1 cm in diameter by 5 cm long cylinder) we used a smaller actuator volume (125 μL) than the one we used for the jumping robot (1.5 mL).

To measure the heat evolved by actuation with compressed air, we assume that the calorimeter is adiabatic, and thus the $q$ we measure is equivalent to the mechanical work, $-w$, done by the pneu-net including frictional losses. We determined $-w$ by injecting 750 μL of air via a syringe pump (Harvard Apparatus), the pressure within the pneu-net increased by ~1 psi and we detected a $q$ = -3.3 mJ (Fig. 3a). After actuation, the pneu-net then slowly leaked air into the larger volume calorimeter cell (via diffusion through the porous silicone[3]) and we measured the heat absorbed (from the expansion of gas and coiling of the polymer chains) during the de-actuation to be $q$ = 2.5 mJ (Fig. 3a). There is thus an 18% loss in converting the potential energy of the compressed gas into mechanical work in the actuator.

In the second experiment, by threading electrical wire into the calorimeter cell, we were able to trigger the combustion of premixed methane/oxygen gas inside the small pneu-net. We filled the volume of the pneu-net with stoichiometric methane/oxygen and triggered an explosion. The heat evolved during the combustion of the gas was $q$ = 350 mJ (Fig. 3b).

The actuation time for compressed air to drive the 125 μL pneu-net is ~ 1 second[4]; the resulting power supplied to the pneu-net is 3.3mJ/1s = 3.3 mW. The time required for an explosion to actuate the small pneu-net is ~10 ms (Fig. 2a-d), yielding 350 mJ/10 ms = 35 W of power. The impulse (change in momentum over time) that results from the ~11,000 fold (35 W/3.3 mW) increase in power causes rapid actuation of the pneu-nets and a jump of the soft robot.

***Thermocouple Description.*** We used a platinum/rhodium thermocouple from Omega Instruments to measure the internal temperature of the pneu-nets during explosive actuation.

***Jumping Height Calculations.*** With a measured initial velocity of 3.6 m/s leaving the ground, the maximum attainable height of an unrestrained robot with a constant mass would be 66 cm (square of the initial velocity divided by twice the constant for gravitational acceleration). Nevertheless, the robot only reached a height of 30 cm because it hit the top of the safety container in which it jumped. When reaching a height of 30 cm, an untethered robot under idealized conditions would arrive in 90 ms and still have an upwards velocity of 2.7 m/s (square root of the difference between the square of the initial velocity and twice the product of the height and constant for gravitational acceleration). In reality, the robot required 150 ms (over 60% more time than that predicted) to reach the height of 30 cm because tethered tubing added mass to the robot as it was rising.

*Adiabatic Flame Temperature*. We also estimated the adiabatic flame temperature with constant pressure (constant enthalpy) for this chemical reaction. The "frozen flame temperature" as described by Kuo [5] was 5,690 K (5,417 $^{o}$C; see Matlab Script). In reality, the adiabatic flame temperature is much less because of dissociations of the products in the combustive reaction. According to Kuo, estimates for "frozen flame temperature" are generally valid for temperatures less than 1,200 K. For cases above 1,200 K, an adiabatic flame calculator (http://elearning.cerfacs.fr/combustion/tools/adiabaticflametemperature/index.php) is helpful. We used a pressure of 1 atm, an initial temperature of 298.15 K, fuel species of $CH_4$, an air molar ratio of 0, and an equivalence ratio of 1, and the computed adiabatic flame temperature was 3,052 K. This value represents a lower limit of temperature because our process is not isobaric.

***Estimate for Average Change in Temperature of the Robot Itself.*** The specific heat of PDMS is 1.46e3 J/(kg K) and the robot is composed of 30 g of silicone, and thus has a net, equilibrated heat capacity of ~45 J/K. The average change in temperature, for the actuation of all its legs is then the difference of the heat generated from the methane combustion (Q; Matlab script below) and the mechanical energy from the jump (U; Matlab script below) divided by the heat capacity. The average change in temperature is thus ~0.41 K for simultaneous actuation of all three legs.

***Cost Estimate for Untethered Jumping Robot.*** The minimum requirements for untethered jumping are one solenoid valve for metering gas (~$25; McMaster-Carr, product # 7877K311), a control board (~$25; Arduino Uno; Mouser Electronics, product #782-A000066), an ignition system (~$50; RC Extreme Power, Inc., single cylinder). The material costs (e.g., silicone, methane, hydrogen peroxide for oxygen, or simply oxygen or air) and battery are negligible compared to the electronics costs.

***Matlab Script to calculate efficiency and heating of a soft robot***

```
%Calculations for Efficiency and Heating of a Soft Robot
%with explosive actuation

g=9.8; %Acceleration due to gravity (m/s^2)
Troom=298; %Temperature of the room (K)
R=8.314; %Universal Gas Constant (J/(mol K))
Proom=101.3e3; %Atmospheric pressure (Pa)

%Robot's jump
m=0.03; %Mass of robot (kg)
h=0.3; %Height of robot's jump (m)
U_robot=m*g*h %Potential energy of robot (J)
%U_robot = 0.0882

%Tubes' jump (Assumes all the material of the tubes gets to the height
%of robots's jump and treats tubes as a dangling chain with center of mass
%halfway up the chain.
h_tubes_fixed=0.3; %Height where end of tubes were held (m)
h_tubes_c=h-(0.5*h_tubes_fixed); %Height of center of mass of tubes before
%combustion (m)
A_tubes=pi*(0.0022^2-0.001^2)/4; %Cross-sectional area of tubes (m^2)
N_tubes=3; %Number of tubes
rho_tubes=1000; %Density of the tubes (kg/m^3)
tubes_m_per_length=N_tubes*A_tubes*rho_tubes; %Mass per unit length of
%tubes (kg/m)
U_tubes=N_tubes*tubes_m_per_length*g*(h-h_tubes_c) %Potential energy of
%tubes (J)
%U_tubes = 0.0399

U_mechanical=U_robot+U_tubes
%U_mechanical = 0.1281

%From Table 1.2 in Kuo
DeltaH_CO2=4.184e3*-94.054; %Enthalpy of formation (J/mol)
DeltaH_O2=0; %Enthalpy of formation (J/mol)
DeltaH_H2O=4.184e3*-68.315; %Enthalpy of formation (J/mol)
```

```
DeltaH_CH4=4.184e3*-17.895; %Enthalpy of formation (J/mol)
DeltaH_combustion=DeltaH_CO2+2*DeltaH_H2O-DeltaH_CH4 %Enthalpy of
%combustion(J/mol)
%DeltaH_combustion = -8.9031e+005
Vol_CH4=0.5e-3; %Volume of combusted methane at 298K and 1 atm (liters)
n_CH4=101.3e3*Vol_CH4*1e-3/(8.314*298) %Number of moles of methane before
%combustion  (mol)
%n_CH4 = 2.0443e-005
Q=-n_CH4*DeltaH_combustion %Energy given off through combustion
%Q = 18.2009

PercentageEfficiency=U_mechanical/Q*100
%PercentageEfficiency = 0.7038
%Estimate for average change in temperature of the robot itself
c_PDMS=1.46e3; %Specific Heat of PDMS (J/(kg K))
AveDeltaT_robot=(Q-U_mechanical)/(m*c_PDMS)
%AveDeltaT_robot = 0.4126
```

**References.**


[1] *CRC Handbook of Chemistry and Physics*, 92nd ed., CRC Press, Boca Raton, **2012**.
[2] K. J. Laidler, J. H. Meiser, *Physical Chemistry*, 2nd ed., Houghton Mifflin Company, Boston, **1995**, pp. 63.
[3] F. Ilievski, A. D. Mazzeo, R. F. Shepherd, X. Chen, G. M. Whitesides, *Angew. Chem. Int. Ed. Engl.* **2011**, *50*, 1890-1895.
[4] R. F. Shepherd, F. Ilievski, W. Choi, S. A. Morin, A. A. Stokes, A. D. Mazzeo, X. Chen, M. Wang, G. M. Whitesides, *Proc. Natl. Acad. Sci. U S A.* **2011**, *108*, 20400-20403.
[5] K. Kuo, *Principles of Combustion*, 2nd ed., John Wiley & Sons, Hoboken, **2005**.

**Fig. S1.** Stress vs. strain curves of Ecoflex 0030 and Dragon Skin 10.

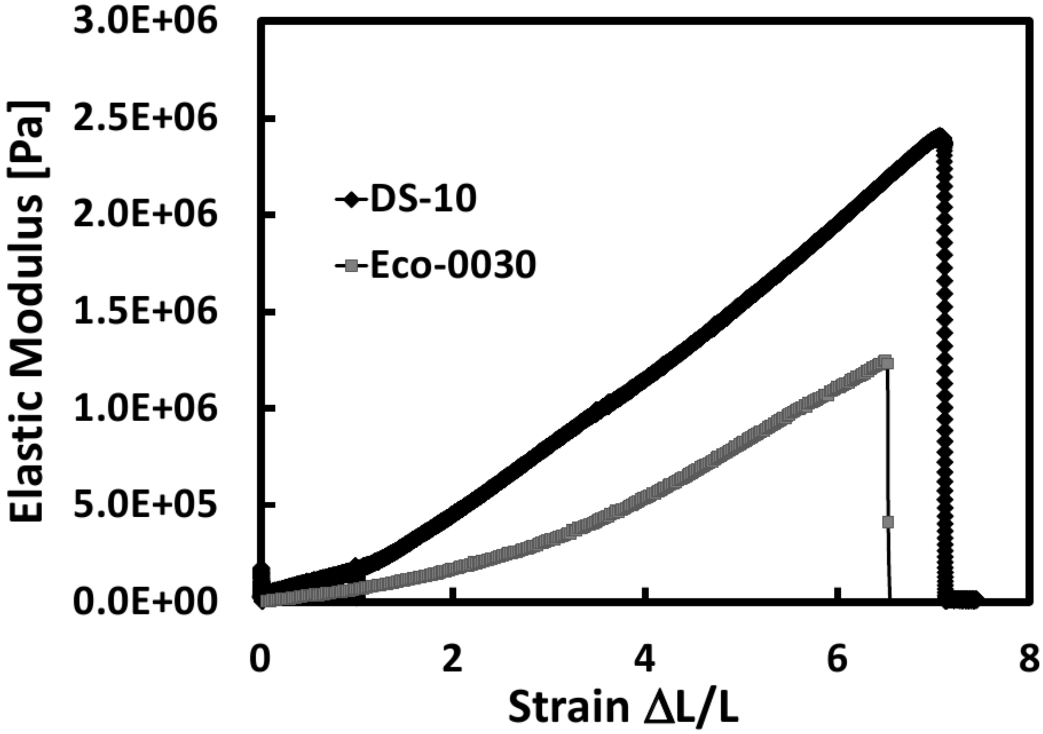


**Fig. S2.** Schematic of an isothermal calorimeter for measuring combustive actuation in a pneu-net. $CH_4$:$O_2$ is pumped into the pneu-net and out through an exit channel. Ignition leads trigger an electrical arc that ignites the gas mixture after the desired amount of equilibration time for the calorimeter. The external water bath is held at constant temperature and the difference in temperatures between the internal and external water baths is used to determine the heat flux during a reaction in the reaction cell (white box, center). This figure was inspired by that in Laidler & Meiser [2].

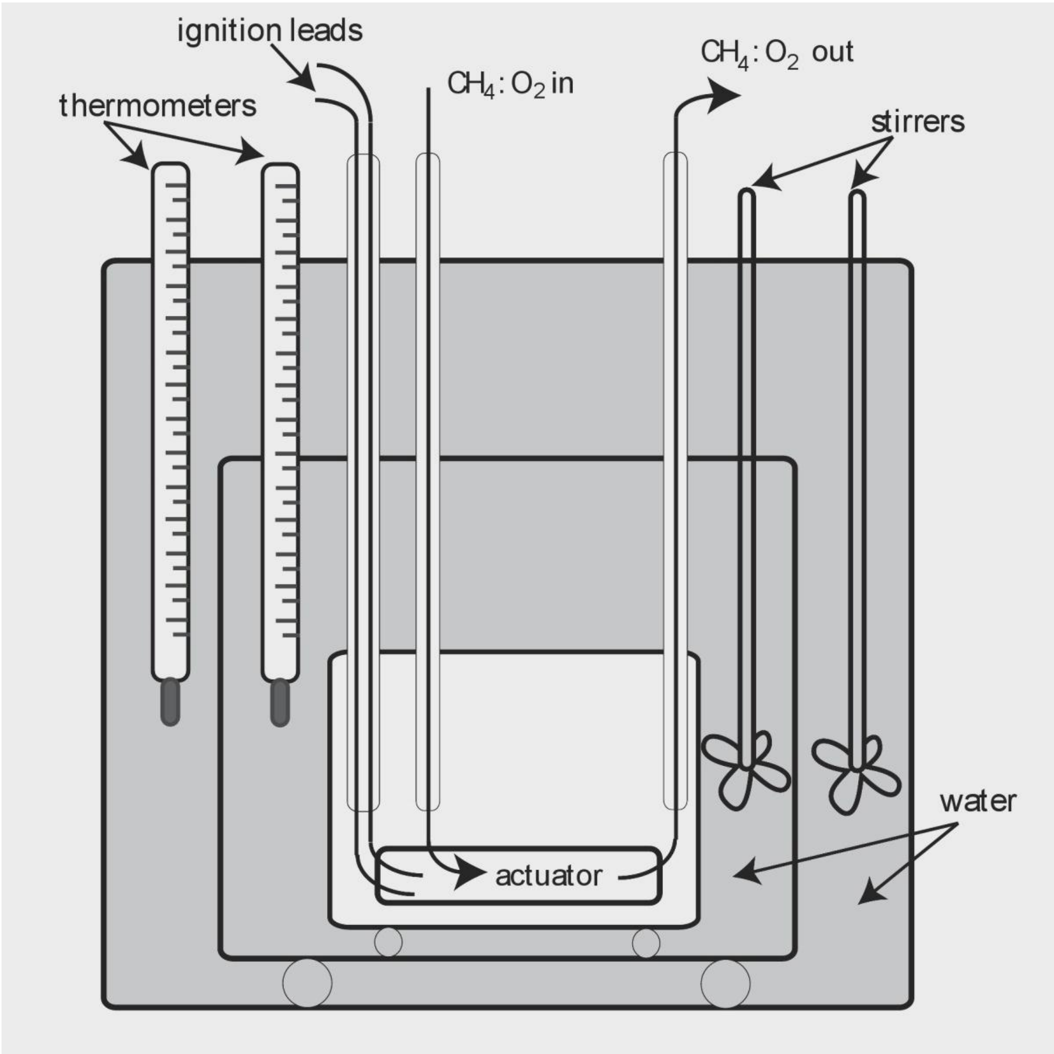
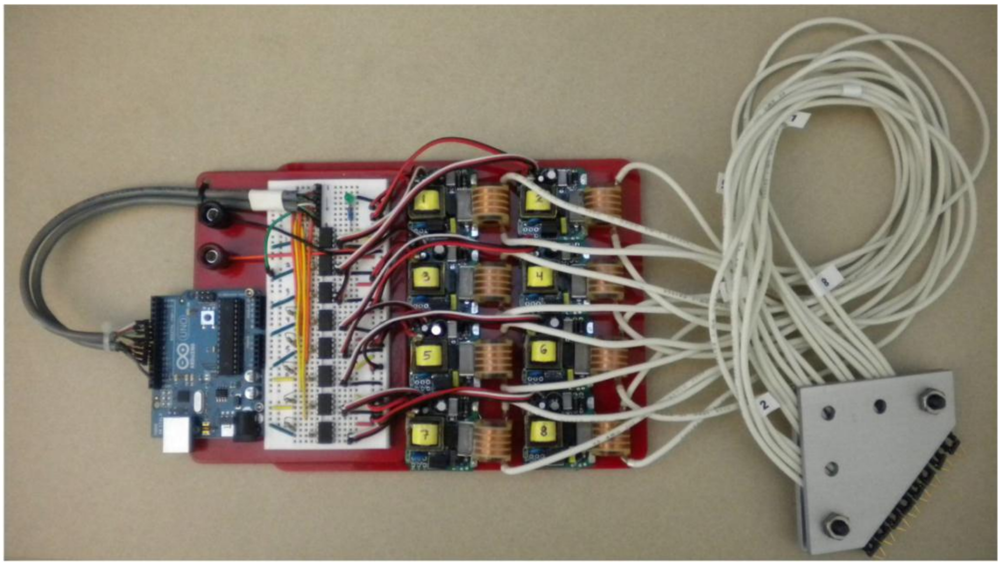


**Fig. S3.** (a) Photograph of ignition system and (b) schematic diagram of ignition system.

(a)



(b)

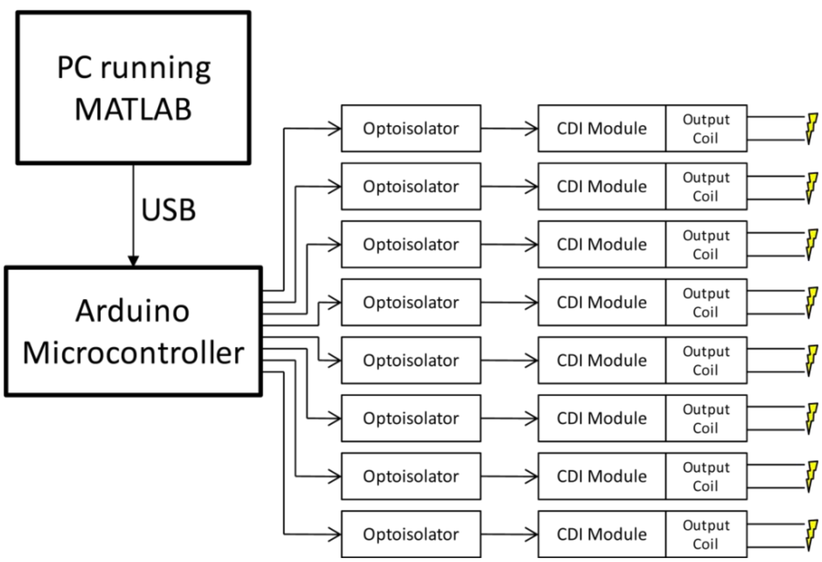
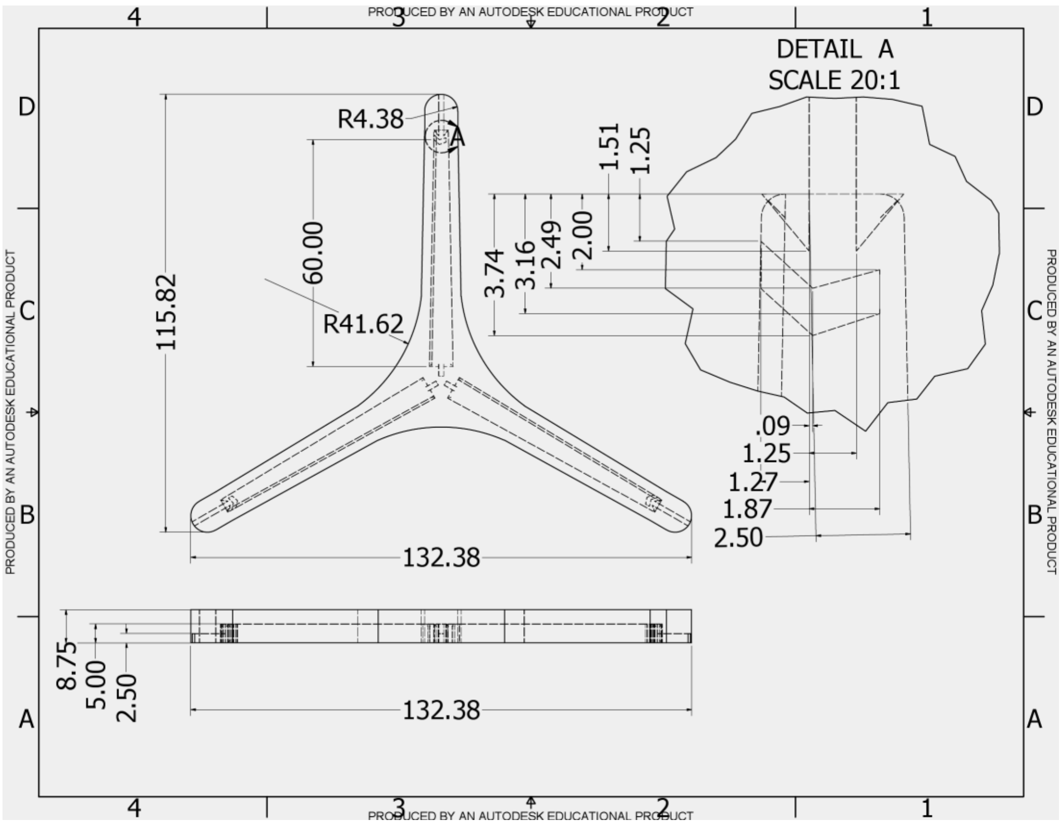


**Fig. S4**. Engineering schematics of jumping robot. Dimensions in millimeters.



**Video S1.** This video demonstrates that the mini explosions are small enough for the robots to be handled by *experienced personnel only*.

https://www.dropbox.com/s/r14d1xkunsq8hat/VideoS1.MOV

**Video S2.** This video demonstrates the passive valve automatically closing and opening during explosive actuation.

https://www.dropbox.com/s/m0x8dt41pivmil6/VideoS2.MOV

**Video S3.** This high-speed video shows the robot jumping over thirty times its height in ~119ms.

https://www.dropbox.com/s/wht6d9fxt7vgx1v/VideoS3.wmv