Simulation and Demonstration of Planar Piezoelectric Soft Robots

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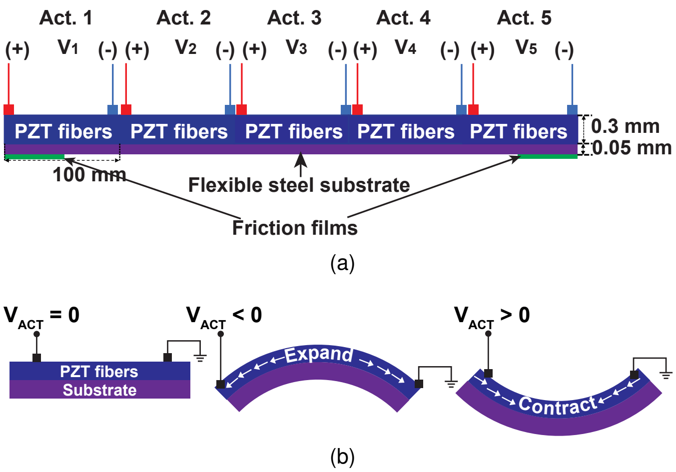

Fig. 1. (a) Cross-section of the demonstrated five-actuator soft robot prototype, 500 mm long and 20 mm wide. A high friction film of 50 mm length is applied on the underside of each end. (b) Mechanism of bending, based on piezoelectric effect, whereby an actuator unit curves concave down (up) due to expansion (contraction) under negative (positive) actuator voltage.

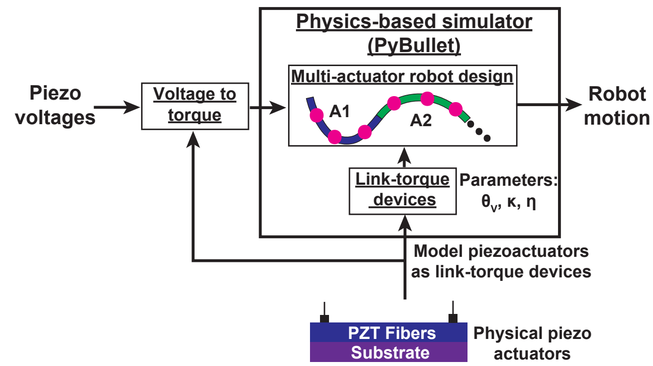

Fig. 2. Simulation framework block diagram, employing motor-link actuators in PyBullet to model arrays of soft-robot actuators.

Soft robots have gathered great interest as of their rich range of shapes and motions, compared to traditional rigid robots. Particularly, electrostatic soft robots have small form factors and fast response speed [2]. However, statics and dynamics, especially when interacting with the environment, pose significant challenges for robust modeling necessary for robot design and control. Most recent work focuses on pneumatic [3], shape-memory, or motor tendon soft robots [4], [5]. Scalable approaches for electrostatic soft robots have been limited. With some examples on single-actuator robot [2] and a roller made of dielectric elastomer actuators [6]. Studies on dynamics of multi-actuator piezoelectric soft robots have been limited.

This work demonstrates a five-actuator piezoelectric soft robot and develops a scalable simulation framework that can reliably predict robot motions. The simulation framework exploits a physics-based rigid robot simulator PyBullet [7] and model the soft actuators as rigid links connected by motors. The simulation framework is validated by comparing its predictions to experimental results, including single-actuator cantilever static displacement and AC oscillations, robot's static shapes, nearly-static "inchworm" motions, and jumping (in vertical as well as vertical and horizontal directions). These motions exhibit complex non-linear behavior. Among them, this abstract demonstrates the vertical jumping of the robot.

The robot consists of five 100-mm-long 20-mm-wide 300-µm-think piezoelectric devices bonded to a single 50-µm-thick layer of steel foil (side view shown in Fig. 1a). A 50-mm-long frictional film is bonded to each end of the robot. The robot rests on the ground and is driven by five external voltages connected by thin compliant wires.

Fig. 1b shows bending mechanism of a single actuator bonded onto a steel foil. When negative (positive) voltage is applied, the piezo device expands (contracts), while the steel foil, due to its high strength, remains fixed in its length. As a result, the whole structure bends concave down (up).

The simulations are integrated into PyBullet (a rigid-robot simulator), including gravity and friction with the ground for time-domain simulations. Fig. 2 overviews the simulation framework. Piezoelectric actuators are modeled as link-torque devices within PyBullet. Our framework converts voltages into motor torques. The resulting link-torque devices then generate the robot's motions. PyBullet solves dynamics with discrete Newton equations for translational and rotational motions.

A key aspect of our work is to model a piezoelectric actuator with multiple rigid links connected by motors (Fig. 3). To represent bending stiffness, piezoelectricity, and damping, we model the torque of each motor proportional to: (1) the deviation of the angle and the target angle of the joint; (2) the angular velocity.

The simulation framework is validated with experiments in multiple cases, including single-actuator cantilever static displacement and AC oscillations, robot's nearly-static inchworm motion as well as jumping (in vertical as well as

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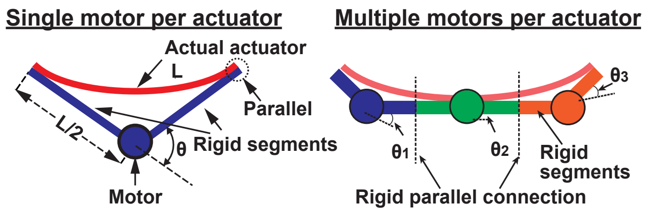

Fig. 3. Modelling of an actuator: an actuator is represented by a series of motors with controlled torque connected by rigid links. Subdividing the actuator into multiple motors with shorter rigid links improves accuracy.

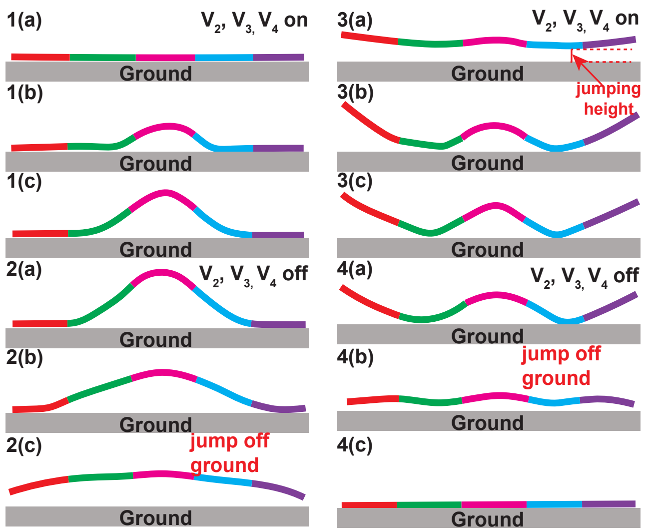

Fig. 4. Robot jumping observed in experiments (from high-speed cameras) due to alternating turning V_2, V_3 and V_4 on and off. The frequency of the voltage cycling is 14 Hz. The whole robot can jump off the ground at least 7.5 mm high, referred as "jumping height" (in step 3(a)).

vertical and horizontal directions). This abstract demonstrates one of them – vertical jumping. It is a 2-phase symmetric jumping motion, where first the middle three actuators are turned on simultaneously to lift the central section, followed by turning them off. Fig. 4 illustrates experimentally-observed shapes (from high-speed cameras) over two driving periods.

The vertical momentum of the midsection is generated by turning them ON (Step 1) and transmitted to other parts along the length of the robot (Step 2) when they are turned OFF, with all parts are lifted off the ground. Steps 3 and 4 repeat Steps 1 and 2. However, as the robot is off the ground at the beginning of Step 3, the robot's motion is different from Steps 1 and 2.

The motion is highly non-linear, as the period of the maximum height is twice that of the driving sequence. Fig. 5a shows experimental results of time-domain movement of the midpoint and the end. Simulation (Fig. 5b) shows great agreement with the experiment, accurately capturing the motion's multiple unusual features.

Fig. 6 shows frequency dependency of the experimental and simulated maximum jumping height off the ground (measured at the robot's lowest point) during a full cycle. The robot can jump as high as ~8 mm. Remarkably good agreement is achieved between simulations and experiments without any curve-fitting parameters.

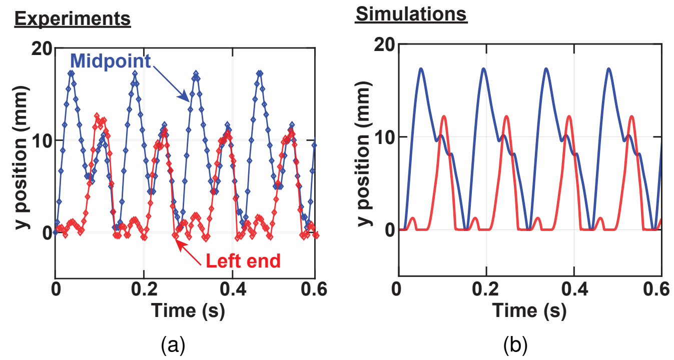

Fig. 5. Time-domain movement of the robot from (a) experiments and (b) simulations, based on tracking the vertical positions of two representative points on the robot (blue line is robot midpoint, red line is robot end point). The applied voltages cycle with frequency of 14 Hz, and the frequency of periodic movement is 7 Hz. Simulations capture the doubling of the period and the phase shift between the time of maximum height for the middle vs. the ends.

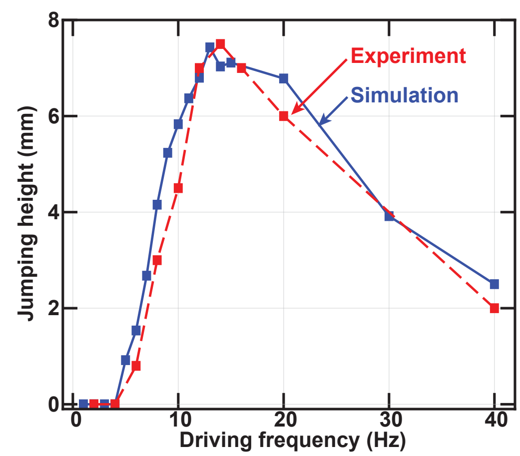

Fig. 6. Jumping height vs. driving frequency using three motors per actuator in simulations, showing excellent agreement between simulations and experiments.

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