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Analytical Model of Locomotion of a Thin-Film Piezoelectric 2D Soft Robot Including Gravity Effects

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Abstract : Soft robots have drawn great interest recently due to a rich range of possible shapes and motions they can take on to address new applications, compared to traditional rigid robots. Large-area electronics (LAE) provides a unique platform for creating soft robots by leveraging thin-film technology to enable the integration of a large number of actuators, sensors, and control circuits on flexible sheets. However, the rich shapes and motions possible, especially when interacting with complex environments, pose significant challenges to forming well-generalized and robust models necessary for robot design and control. In this work, we describe an analytical model for predicting the shape and locomotion of a flexible (steel-foil-based) piezoelectric-actuated 2D robot based on Euler-Bernoulli beam theory. It is nominally (unpowered) lying flat on the ground, and when powered, its shape is controlled by an array of piezoelectric thin-film actuators. Key features of the models are its ability to incorporate the significant effects of gravity on the shape and to precisely predict the spatial distribution of friction against the contacting surfaces, necessary for determining inchworm-type motion. We verified the model by developing a distributed discrete element representation of a continuous piezoelectric actuator and by comparing its analytical predictions to discrete-element robot simulations using PyBullet. Without gravity, predicting the shape of a sheet with a linear array of piezoelectric actuators at arbitrary voltages is straightforward. However, gravity significantly distorts the shape of the sheet, causing some segments to flatten against the ground. Our work includes the following contributions: (i) A self-consistent approach was developed to exactly determine which parts of the soft robot are lifted off the ground, and the exact shape of these sections, for an arbitrary array of piezoelectric voltages and configurations. (ii) Inchworm-type motion relies on controlling the relative friction with the ground surface in different sections of the robot. By adding torque-balance to our model and analyzing shear forces, the model can then determine the exact spatial distribution of the vertical force that the ground is exerting on the soft robot. Through this, the spatial distribution of friction forces between ground and robot can be determined. (iii) By combining this spatial friction distribution with the shape of the soft robot, in the function of time as piezoelectric actuator voltages are changed, the inchworm-type locomotion of the robot can be determined. As a practical example, we calculated the performance of a 5-actuator system on a 50-µm thick steel foil. Piezoelectric properties of commercially available thin-film piezoelectric actuators were assumed. The model predicted inchworm motion of up to 200 µm per step. For independent verification, we also modelled the system using PyBullet, a discrete-element robot simulator. To model a continuous thin-film piezoelectric actuator, we broke each actuator into multiple segments, each of which consisted of two rigid arms with appropriate mass connected with a 'motor' whose torque was set by the applied actuator voltage. Excellent agreement between our analytical model and the discrete-element simulator was shown for both for the full deformation shape and motion of the robot.

Keywords : analytical modeling, piezoelectric actuators, soft robot locomotion, thin-film technology
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