Towards Microrobots with Insect-Like Dexterity: A Computational Study

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ABSTRACT

In this paper we explore the piezoelectric effect to operate as "solid state muscles" to facilitaterobust insect-like dexterity for microscale robotics. Prior microrobotic efforts include complex hinges and sliders that can wear from friction; comb drives that can jam from environmental particulates; slow-moving parts; and the inability to traverse uneven terrain. In the presenteffort, we advance microrobitic technology towards insect-like dexterity. This includes leading to microrobots that are able to walk, run, and jump in various directions; continue to walk once flipped upside down on their back; traverse through harsh terrains such as sand; pick up, carry, and place relatively large loads; withstand large impacts or accelerations; recharge using energy-scavenging; no frictional parts to wear out; and an extraordinary length of lifetime.

Keywords:microrobot, microid, piezoelectric, robot, insect, biomimetic.

1. INTRODUCTION

A critical and elusive milestone inmicroscale roboticshas been to develop a mechanism to facilitate insect-like mobility. If achieved, the benefits include applications in surveillance, search and rescue, pest control, micro assembly, environmental monitoring, and many more.

A few recent and broad developments in microrobotics include the following. In 2005, Hollar, Flynn, Bergbreiter, and Pister reported on two-degree-of-freedom control of a microrobotic leg in a five-mask silicon-on-insulator (SOI) process [1]. The effort was successful in integrating several complex mechanisms including large comb drive arrays, microscale hinges, sliders, clutch, and transmission. In 2006, Donald, Levey, McGray, Paprotny, and Rus reported on an untethered scratch drive actuator that was able move forward and make left turns on a globally-controlled interdigitated electrode platform [2]. The effort was successful in reducing the size of a microrobotic system, in traversing complex planar paths, and in independent control of two microrobots on a single platform. In 2007, Bergbreiter and Pister presented initial results on a jumping microrobot, where an inchworm motor stored potential energy in an elastic band, which when released, propelled the microrobot several centimeters [3]. The effort promoted the use of jumping as an efficient means of mobility at the microscale.In 2003, Hollar, Flynn, Bellew, and Pister reported on an autonomous two-legged microrobot in [4]. The effort was successful in incorporating onboard control and power supply. In 2006, Chen, Suh, Kovacs, Darling, and Bohringer reported on the control a 3DOF thermally-actuated walking microrobot [5]. The effort was successful in demonstrating the control of 512 thermal bimorph actuator legs using a wave-like gate to propel it up to a speed of $250 \mu m/s$. It has a load carrying capability of 4 grams, about 10 times its mass. As a last example, in 2008, Floyd, Pawshe, and Sitti reported on an untethered microrobot that is capable of moving on arbitrary surfaces by the stick-slip motion of passive magnetic material controlled by an external field [6]. The effort was successful in showing a microrobotquickly positioning a number of microscopic particles. In [7], Sitti gives an overview of other advances in micro and nanoscale robotics.

Although there have been substantial advances, the discovery of a mechanism that allows microrobotsto maneuver through the harsh terrain that is commonly encountered by insects has yet to be realized. Our effort toward this goal is presented in this paper as follows. In Section 2 we overview the piezoelectric mechanism that we propose for low-power biomimetic dexterity. In Section 3 we explore various capabilities that stem from this technology.And we summarize our findings in Section 4.

2. PIEZOELECTRIC MECHANISM

As we alluded to in the previous section, microrobotics is broadly defined. Here, we investigate a particular branch that we choose to call *microids*. We define a microid as an autonomous microrobot with insect-like dexterity in mobility (crawl, jump, fly) and task ability (lift, push, pull loads).

Locomotion. Although the microrobotsdiscussed in the previous section have the ability to move in at least one direction under controlled conditions, they currently do not appear to possess the capability to maneuver in terrain that is commonly encountered by insects. For dynamic stability in uneven terrain, insects typically use a tripod gate for locomotion. This tripod gate applies to 6-legged insects as well as insects with many more legs (also known as a metachronal wave gate). Each leg of an ant has three joints. Implementing similarly functioning joints in MEMS appears to be a daunting task. For instance, current microscale hinges can suffer from particulate contamination, frictional wear, and frictional energy loss. And it is not yet clear how many cycles can such joints withstand. Micro gears have similar frictional issues. J. Allen [7] states that many of Sandia's complex MEMS with gears can only operate continuously for minutes or hours before failure due to frictional wear.

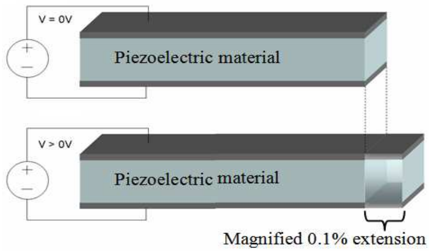


Figure 1: The small deflection of a piezoelectric flexure. By applying 10s of volts, the flexure typically expands or contracts only about a thousandth of its initial length. That is, a flexure that is 100 microns long will expand or contract about 0.1 microns.

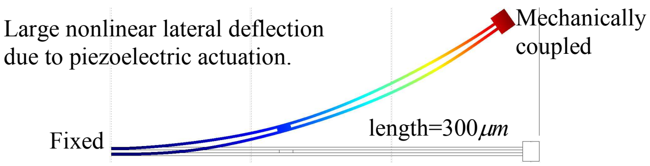


Figure 2: Nonlinear deflection simulation by finite element analysis. Although the upper-most flexure contracts by a thousandth of its initial length, and the lower-most flexure extends by a thousandth of its initial length, by mechanically coupling the pair of flexures at the far right end, and fixing the left ends, a large deflection of 99μm (about a third of its length) is achieved. The central mechanical couple seen on the structure constrains the flexures from bulging away from each other. Otherwise, the deflection would be about 47μm. The material is PZT, the square cross section of each flexure is 2μm, the length is 300μm,and 40V is applied.

Therefore, instead of using mechanisms with contact friction, we propose the use of piezoelectric flexures (*solid-state muscles*) that are able to contract and expand minutely along their axis, but deflection significantly laterally.

Piezoelectric effect

Although piezoelectric actuation had been thought toproduce too short of a stroke to be useful inmicrorobots, we have discovered a way to exploit the piezoelectric phenomena to achieve large (10s of microns) two degree of freedom (DOF) deflection per appendage, for fast-response insect-like dexterity.

In Figure 1, we show a depiction of a simple piezoelectric flexure. Piezoelectric material is a dielectric that is able to deform when it is subject to an electric field. Conversely, the material is able to generate a voltage when it is subject to an applied mechanical pressure that causes deformation, which we plan to explore for energy harvesting. By applying a thin conductive layer on the top and bottom of the piezoelectric material, the deformation of the flexure can be controlled by a voltage source. Voltage causes the piezoelectric flexure to either expand or contract depending on the polarity of the applied voltage. The direction of deformation depends on the type of piezoelectric material. In our present application, our preferred deflection is along the axial direction. The piezoelectric deformation due to 10s of volts is typically on the order of a thousandth of its initial length. Such a small deflection may explain prior reluctance of its use in microrobotics.

However, by coupling a pair of piezoelectric flexures, large lateral deflections are possible. In Figure 2 we show a nonlinear finite element analysis (FEA) simulation of a pair of piezoelectric flexures that are mechanically coupled on the far right end and mechanically fixed on the far left end. We found that by additionally coupling the flexures at an intermediate position, the nonlinear large deflection almost doubles at 40V. This doubling is the result of constraining the flexures from flaring away from each other. In Figure 2, we applied a voltage of 40V to achieve a nonlinear deflection of 99μm. The flexures are 300μm long, 2μm wide, 2μm thick, with a 2μmgap between the flexures. The piezoelectric material is PZT. In this paper we do not optimize the geometric design or material properties to achieve the greatest deflection per applied voltage. Such will be the subject of our subsequent efforts.

The axial deformation that produces a large lateral deflection is similar to the axial deformation that takes place in electro-thermal actuators, see [9]; however, electro-thermal actuators lose a significant amount of power through Joule heating and the material does not actively contract. The coupled extension + contraction nearly doublesthe deflection of our actuator for given applied voltage.

Appendages with two degrees of freedom

By extending this piezoelectric actuation idea from planar deflection to include out-of-plane deflection, we are able to achieve 2 DOF motion. This is accomplished by coupling a third piezoelectric flexure to the pair shown in Figure 2. We show the resulting triad of piezoelectric flexures in Figure 3. By controlling the magnitude and polarity of the applied voltage, various 2 DOF (in-plane + out-of-plane) deflections are possible. This triad of piezoelectric flexures forms a single appendage (leg or mandible), where the right end is the foot, and the left end is the hip, which is fixed to the body of the robot. In Figure 4 we superimpose a few voltage-induced deflections of the leg. Since the appendage has an asymmetric cross section, some deflections may result in a small twisting of the foot and a small cross-axis deflection that may not be apparent in the figures following figure.

3. CONFIGURATION AND PERFORMANCE

Configuration of the microidmicrorobot

Using six appendages for legs, and twoappendages for mandibles, we show a fully-assembled microidmicrorobot in Figure 5 in itsunactuated state. We include the expected weight of a central processing unit (CPU) and energy storage unit on its back. When realized, the CPU may be integrated into the robot using standard technologies. And recently, microscale energy storage has become a successfullyactive area of research in the MEMS field.

Upon actuating all appendages, we simulate the microid standing on all legs with a clearance of about 100microns between the body and ground. See Figure 6. To account for the weight of the CPU and energy storage unit, we have included the effect of the earth's gravitation in all of our

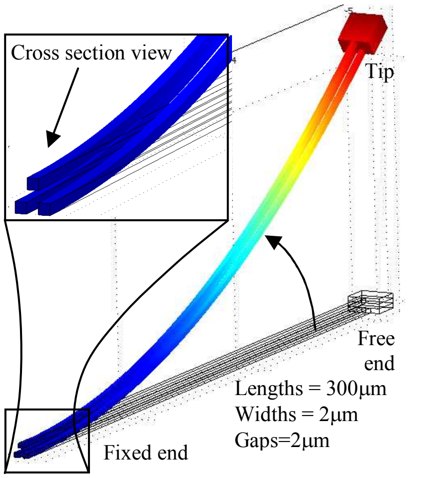


Figure 3:A solid state piezoelectric appendage. Triple-flexure bundle of piezoelectric actuators, which are mechanically coupled at the ends. Small axial extensions + contractions produce large lateral deflections.

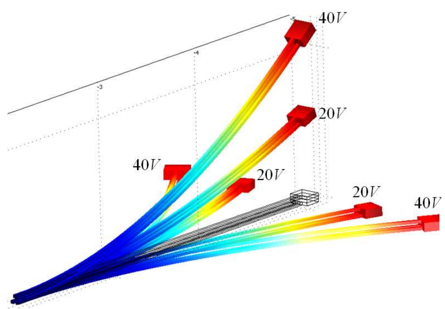


Figure 4: Multiple deflections of the appendage in Figure 3 are superimposedhere to emphasis its two degrees of freedom.

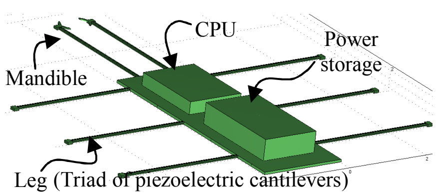


Figure 5: An integrated system forming a microrobot. Six appendages (from Figure 4) are used for the legs and two appendages are used for the mandibles. The robot is shown in the zero unactuated state.

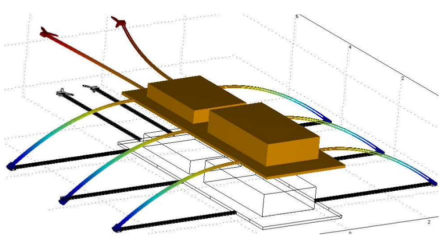


Figure 6: Microrobot in an actuated state. The zero state from Figure 5 is superimposed underneath it. 40*V* is applied for actuation.

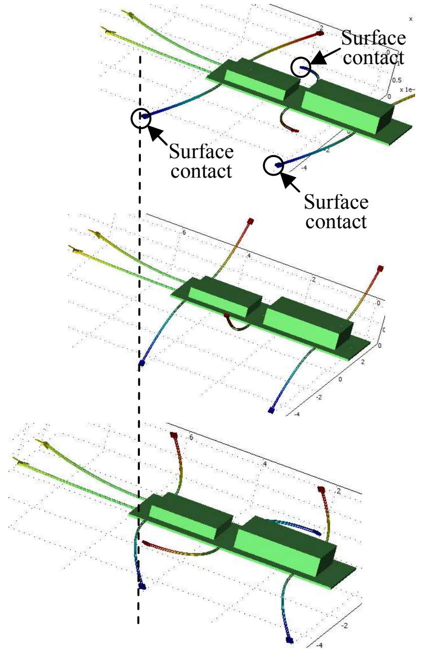


Figure7: Walking or running sequence of a single step. The microrobot travels using a tripod gate. Pin-joints on three of the feet emulate surface contact in this finite element analysis simulation.

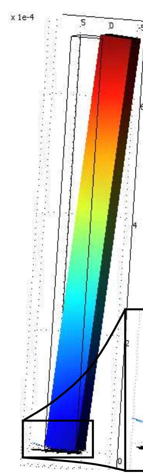
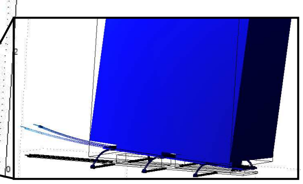



Figure 8: Simulation of a load being carried on the back of the microrobot. The tower of silicon weighs 3500 times the weight of the microrobot. Using one step at a time, the microid is able to walk, clearing the ground.

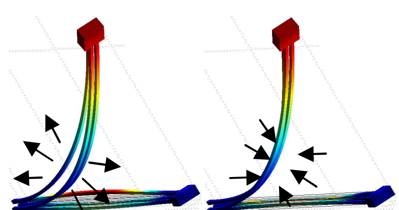


Figure 9: Modeling of particulate contamination. (Left) a particulate lodged within the triad of flexure that form an appendage is modeled as forces causing the flexures to spread apart. An applied actuation voltage shows that mobility is still viable. (Right) the opposite effect where the beams are squeezed together. Theappendages remain operational.

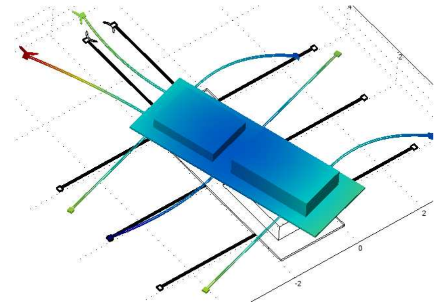


Figure 10:A simulation of the microrobot turning at a point, using a tripod stages. Its initial state is superimposed underneath. Slider and pin joint constraintson the feet emulate surface traction.

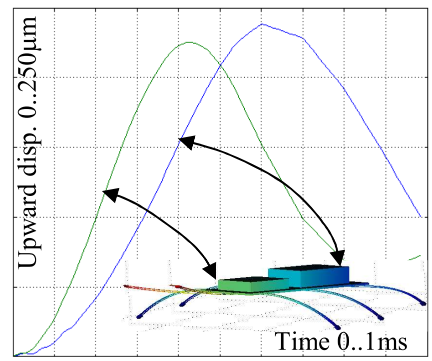


Figure 11: Directional jump analysis. Upward displacement versus time for the front and back of the microrobot. A 40*V* step is applied resulting in a jump height of about 2.7cm. By strategically applying voltages of varying amounts and times, the robot is able to jump in various directions.

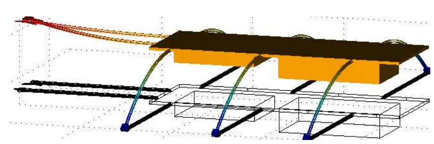
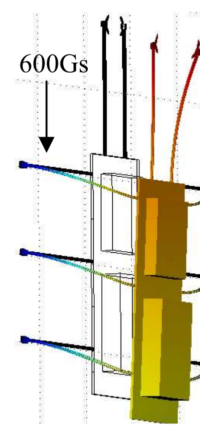


Figure 12: If the microrobot lands on its back, it is just as mobile. Its voltage polarity is simply reversed. Performances abilities such as carrying loads, jumping, turning, etc. are still viable.



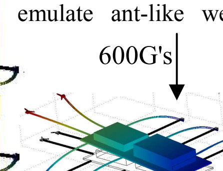


Figure 13: An acceleration of 600 G's is applied vertically in both simulations. Thefeet of the robotare constrained with pin joints to emulate ant-like wet

simulations. Within our FEA model, a surface that the microid stands on is emulated by applying pin joints on two of the left legs and a planar slider joint on one of the right legs. This allows the legs to slightly close in on each other as with a typical stance.

Performance

In this section we discuss several practical performance aspects of the microid. The mandibles are able to spread apart, touch, bend up, or bend down depending on the applied voltages. Similarly, the legs of the microidare able to independently move left, right, up, or down with varying degrees and speed. With all legs working together, the microid is able to walk in a tripod fashion, as we simulate in Figure 7. In the figure we show a sequence of intermediate phases of a single step being taken. When walking or running in a tripod gate, two sets of three legs are simply actuated by identical voltage functions that are 180 degrees out of phase. The boundary conditions applied to the feet are 3 pin joints to emulate surface contact of 3 legs at a time.

It is well known that ants are able to carry hundreds of times their own body weight. This is possible because mass scales as length cubed. That is, if the geometry of an object reduces by a factor of 10, then its mass reduces by a factor of 1000. Similarly, as we show in Figure 8, our microid is able to carry a tower of silicon that is 3500 times its own weight. With such a load on its back causing its legs to nearly buckle, the microid is still able to clear the surface by a few microns. To walk with such a heavy load and still clear the surface, the microid may take one step at a time such that at least five legs are continuously supporting the load at each instant.

In order to operate outside of a controlled laboratory environment, microrobotsshould be able to operate in the midst of dust, sand, water, etc. In Figure 9 we simulate the effect of a small particulate of dust or sand lodged between the triad of piezoelectric flexures of a single leg. We emulate this particulate by applying equivalent particulate forces upon the flexures such that they separate. We find that the performance of the leg is not significantly affected. And by pressing the flexures together, the performance of the leg is not significantly affected as well. Regarding water, water has littleeffect on the piezoelectric effect. However, without a thin layer of cladding on the electrodes of the piezoelectric flexures, the energy source may quickly drain in conductive aqueous environments.

Although the microid is able to walk or run along a curved path, it is also able to rotate about a point by applying a particular combination of voltages to the legs. We simulate the microid turning at a point in Figure 10. Surface traction is emulated using pin joints and sliders on three of the legs. The other three legs are repositioning themselves above ground. A complete turn is accomplished with several steps.

As previously mentioned in the introduction, jumping at the microscale can be an efficient mode of travel. For instance, jumping can be advantageous if an obstacle is too large to crawl over, or jumping onto a moving object can save travel energy and travel time. In Figure 11 we show our transient analysis results of our microid jumping. Its initial position is the zero unactuated state. Upon applying a $40V$ step function, the legs quickly respond and raise the microid off of the ground a height of $2.7cm$ with our present design. With jumping or traversing uneven terrain is the strong possibility of the microid ending up on its back. Due our dexterous actuation mechanism, by reversing the polarity of the legs, the microid is able walk up-side-down, or preferably use its legs to flip over so it is right-side-up. This is an ability that insects cannot do. See Figure 12.

As a last example, we explore the microid's ability to withstand large forces. In Figure 13 we show the microid subject to 600 G's of acceleration in both in-plane and out-of-plane directions. We apply pin joints on the feet to emulate the wet adhesion ability of ants. The in-plane demonstration may also be used as an indicator on how the microid fairs in strong wind speeds of $125m/s$(or 279 miles per hour – about twice the speed of tornado winds). The amount of foot adhesion necessary to withstand such acceleration or wind is about $1.7\mu N$ of force. In addition, due to the microid's solid state construction, it should be able to withstand large out-of-plane externally applied forces. For instance, due to its small size, the net force a microid would experience by being stepped on by a $200lbf$ person, or rolled over by $3500lbf$ car, is about $0.8mN$ and $15.1mN$ respectively.

4. CONCLUSION

In this paper weproposed a novel piezoelectric mechanism to achieve insect-like dexterity in a microrobot. Performance of the microrobot was explored using finite element analysis that included the physics of piezoelectric material, large nonlinear deflections, and gravitation. Ground surface support and traction was emulated using a combination of pin joints and sliders. The weights of a CPU and an energy storage unit were included. We applied actuation voltages directly to the microrobot appendages for various performance analyses. Such analyses included walking or running, supporting large loads, functioning with particulate contamination, turning at a point, jumping, walking up-side-down, and withstanding large externally applied forces. As a first step, our exploration indicated that this novel technology may lead to the realization of microrobots with the ability to operate autonomously and robustly in environments typically encountered by insects. As a second step, we are fabricating appendages for proof-of-concept and characterization.

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