Development of a Piezoelectrically-Actuated Mesoscale Robot Quadruped

Michael Goldfarb, Michael Gogola, Gregory Fischer
Department of Mechanical Engineering
Vanderbilt University
Nashville, TN 37235

Ephraim Garcia
Defense Sciences Office
DARPA
Arlington, VA 22203

Corresponding Author:

Michael Goldfarb, Ph.D.
Associate Professor
Department of Mechanical Engineering
Vanderbilt University
Box 1592 Station B
Nashville TN 37235
Tel: (615) 343-6924
Fax: (615) 343-6925
Email: goldfarb@vuse.vanderbilt.edu
Abstract

This paper describes a minimalist mobile robot design approach that offers a high locomotive efficiency, and is therefore well suited to mesoscale robot design. The authors have incorporated this approach into the development of a dynamically controlled piezoelectrically actuated mesoscale robot quadruped. The design described utilizes a lightly damped skeletal structure that generates locomotion when vibrationally excited at a skeletal resonance by two piezoelectric unimorph actuators. The skeletal structure consists of four articulated legs used to produce a trot type gait. Each articulated leg moves in two degrees of freedom to create elliptical foot motions that enhance locomotion efficiency and rough surface capability. Directional control is achieved by tuning each leg to a slightly different resonant frequency, so that differential control of leg amplitude can be achieved by modulation of the actuator excitation frequency. Compact power electronics have been developed and self-powered (i.e., battery-powered) operation has been demonstrated. This paper describes the design of the robot quadruped, which has a footprint that measures 9 cm x 6.5 cm and weighs 51 grams without the electronics and 104 grams with them. Data is presented that characterizes the average speed and typical power consumption of the robot at various excitation frequencies.

Keywords

Piezoelectric actuation, mobile robot, quadruped, crawling, vibration, resonance
1 Introduction

A mesoscale device is generally considered to be one that contains length scales on the order of millimeters to centimeters. Since volume scales with the cube of a geometric scaling, mesoscale machines contain significantly less volume than their conventional scale counterparts. The disproportionate decrease in volume in a mesoscale machine results in two significant challenges. The first is limited design space, which in turn suggests the use of simple and minimalist designs. The second is that, since electrochemical battery energy densities are essentially constant, the amount of available energy will decrease with the cube of size. A mesoscale robot that is geometrically similar and smaller than a conventional scale robot therefore has significantly less available energy to travel a given distance. For example, a battery-powered mesoscale robot that is designed as a one-tenth-scale version of a conventional-scale robot would ideally travel a distance ten times shorter than its larger counterpart. Assuming that the locomotive efficiency remains invariant, however, the smaller version will travel a distance one thousand times shorter. The smaller robot will therefore have a range that is one hundred times smaller than the larger, relative to its own dimensions. The development of mesoscale robots is therefore aided significantly by the implementation of simple design approaches that result in efficient locomotion. This paper describes such a design approach. The approach, called elastodynamic locomotion, utilizes a lightly damped skeletal structure that generates efficient locomotion when vibrationally excited near a skeletal resonance.

1.1 Background

A considerable amount of work has been conducted in the design of autonomous conventional-scale robot quadrupeds. These designs generally incorporate independent control of the motion of each leg and multiple sensors for gathering information regarding leg
motion and terrain. These features, along with on-board computational ability, afford these machines the ability to traverse various terrains and obstacles. Such machines are generally not appropriate for implementation at the mesoscale, since the required complexity (e.g., number of actuators and sensors) is mismatched to the previously mentioned volume constraints of a mesoscale device. Further, the energetically non-conservative nature of closed-loop control of leg motion is additionally mismatched to the previously described need for efficient locomotion.

Though the authors are not aware of other previously developed piezoelectrically actuated quadrupeds, other researchers have incorporated piezoelectric actuation into the development of small-scale mobile robots. De Ambroggi et al. have developed piezoelectrically actuated robots that have a footprint of approximately 2 cm by 2 cm [1]. These robots are actuated by two legs, which each consist of two serially mounted piezoelectric bimorphs, and also incorporate a third passive leg, which is used for stability. Since the piezoelectric actuators are utilized in a direct drive sense (i.e., no displacement amplification), the robots are generally confined to operate on smooth surfaces. Martel et al. are have reported on the development of a twelve degree-of-freedom piezoelectrically actuated three-legged robot with a footprint of approximately 2 cm by 2 cm [2]. This robot also incorporates no displacement amplification of the piezoelectric actuators, and is therefore also confined to operate on smooth surfaces.

Kawahara et al. have developed a piezoelectrically actuated in-pipe wireless robot [3]. The robot is cylindrical in shape with a diameter of approximately 1.5 cm and a length of approximately 4 cm. This robot incorporates multi-layered piezoelectric bimorphs as actuators and incorporates an on-board energy converter to convert microwave power
traveling in the pipe into DC electric power. Other than the work presented herein, this is the first wireless (i.e., not power-tethered) piezoelectrically actuated robot of which the authors are aware.

Several researchers, such as Higuchi et al. [4] and Breguet and Renaud [5], have additionally developed stepping-type or inertial-drive-type piezoelectric motors, which can be considered similar to small-scale mobile robots. These types of motors are generally not designed to be self-powered, and since they incorporate no displacement amplification of the piezoelectric actuators, they are confined to operate on smooth surfaces.

The robot design described in this paper is a piezoelectrically actuated quadruped that was designed to be capable of self-powered operation and to accommodate reasonably rough surfaces. The minimalist philosophy upon which the robot design is based was motivated in part by the work of Yasuda et al., who have developed a microrobot that is actuated by a vibration energy field [6]. Specifically, they developed a passive silicon micromachined device that measures approximately 1.5 mm by 0.7 mm. The silicon robot sits on a vibration table, which acts as the energy and control source. Vibrationally exciting the robot through the table excites each leg, which in turn generates contact between the robot and the table, which pushes the robot along. Each limb of the device is designed to exhibit resonance at a different frequency from the other limbs. The motion of the passive silicon device can therefore be controlled by superimposing sinusoidal excitation of the respective leg resonant frequencies onto the robot, and thus differentially controlling the amplitudes of leg motion. The work presently in this paper is similar to the approach of Yasuda et al., but instead utilizes two-degree-of-freedom leg motion and incorporates the energy and actuation source on-board the robot.
1.2 Elastodynamic Design Approach

The design described incorporates a lightly damped skeletal structure that generates locomotion when vibrationally excited at a skeletal resonance by piezoelectric actuators. This primarily elastic approach to locomotion provides two significant advantages. First, since the motion is elastic, it is energetically conservative (i.e., the acceleration and deceleration of each limb requires no net power). The combination of a piezoelectric ceramic, which exhibits low energy dissipation, and the use of resonance, which is energetically conservative, results in a highly energetically conservative device. Second, utilizing a lightly-damped structure enables control of limb amplitude by frequency shifting (as was demonstrated by Yasuda et al.), which minimizes the number of independent actuators required for control of the robot. Specifically, by tuning the resonant frequencies of the legs on each side of the skeleton to slightly different frequencies, the leg amplitudes can be differentially controlled by slightly shifting the frequency of excitation. This concept is illustrated in the frequency response diagram shown in Figure 1. A left or right turn can be achieved by shifting the excitation frequency to match the resonant frequency to the limbs on the side of the vehicle that is opposite the desired turning direction. Straight motion is achieved by exciting the system at a frequency in between the left and right side resonances, whereby both sets of legs (i.e., left and right sides) operate slightly out of resonance, but with an equal degree of amplification. Resonant (or near-resonant) operation therefore provides a mechanism for dynamically controlling a robot, which in turn minimizes the requirement for independently actuated degrees of freedom.

Finally, in addition to providing for efficient locomotion and a minimum actuator configuration, utilization of an elastic mechanism (i.e., a flexure based metallic skeleton)
eliminates the need for roller or journal bearings and therefore results in a more environmentally robust system, providing immunity from environmental contaminants such as sand and dust.

1.3 Piezoelectric Ceramic Actuation

The use of piezoelectric (PZT) actuators provides several beneficial features. First, PZT is an elastic actuator, and therefore well suited for the elastodynamic approach. Second, PZT is a highly energetically conservative means of electrical to mechanical energy transduction. Specifically, the only significant mechanisms of dissipation are an electrical hysteresis, which dissipates approximately 10% of the input energy per cycle of actuation, and mechanical damping in the ceramic, which typically exhibits a damping ratio of approximately 0.5 [7]. Third, PZT has amongst the highest volume specific power of any electrical to mechanical transduction mechanism [8]. Finally, PZT also has favorable force scaling characteristics relative to other common transduction mechanisms [9].

Though PZT provides significant benefits as an actuator, it also has some significant drawbacks relative to mesoscale robotic applications. Perhaps the most limiting of these is that it typically provides relatively small displacements. Polycrystalline piezoelectric ceramic typically provides material strains on the order of 0.1%. In a direct drive sense, a 2 cm long PZT stack will provide only 20 microns of displacement. If a mesoscale robot is to traverse reasonably rough surfaces, the small displacements provided by the PZT ceramic must be amplified by significant mechanical amplification mechanisms. From a power perspective, though PZT actuation is volumetrically power dense, the power is provided in a high force and low displacement fashion, relative to that required by a mesoscale quadruped. Optimal use of the power provided by a PZT actuator therefore requires a large mechanical
transmission to convert the high force, low displacement work into relatively low force, high displacement work. The amplification (or transmission) mechanisms utilized to match the actuator with the work output of the robot should additionally be energetically conservative in order to maintain the energetic benefits of the PZT actuator.

The primary mechanisms of PZT displacement amplification are structural amplification, kinematic amplification, and dynamic amplification. Specifically, structural amplification is that which results from utilizing a configuration of actuator that amplifies the strain output of the PZT ceramic, and in the design described herein takes the form of a unimorph actuator. Kinematic amplification is achieved through use of compliant mechanism-based linkages. Finally, dynamic amplification utilizes the frequency response characteristics of the elastic transmission, and specifically operates the device at or near the primary resonance of the transmission. The authors incorporate all of these mechanisms into the design of the elastodynamic robot in order to maximize the displacement output of the PZT.

Another significant drawback of piezoelectric actuation is the relatively high voltage required for actuation. Just as the mechanical (output) power of the PZT actuator is in a different regime from that required by a mesoscale mobile robot, so also is the electrical (input) power in a different regime from that provided by a typical electrochemical battery. Just as a large and efficient mechanical transmission is desired to convert the PZT output power to a useful regime, so also is a large and efficient electrical transmission desired to convert the power from a battery into that required by the PZT. This issue is addressed in the Power Electronics section of this paper.
2 Prototype Design

The elastodynamic robot quadruped is shown in Figure 2. The robot incorporates two piezoelectric unimorph actuators (manufactured by Face, Inc.) that drive four legs in a trot type gait. Each leg contains two degrees of freedom and is configured as an inertially decoupled five-bar linkage. The two actuators are excited with a sinusoidal voltage of the same amplitude and frequency, but shifted in phase by approximately 90 degrees. The robot measures approximately 9 cm long, 6.5 cm wide, and 5 cm tall, and weighs 51 grams without the on-board power electronics or battery. A description of the design and design morphology follows.

2.1 Drive System

Though robot quadruped locomotion can be achieved with curvilinear foot motion (i.e., each foot moves forward and backward along the same path, relative to the robot reference frame), use of a closed path (e.g., an elliptical path) generally provides greater mobility (e.g., ability to traverse rough surfaces) and greater efficiency (i.e., less frictional energy loss due to sliding). Due to these advantages, the objective of the robot quadruped design was to obtain closed path foot motions for each leg, subject to the minimalist elastodynamic design philosophy previously described.

The minimum number of actuators for any active device is one. Obtaining a closed path trajectory in the case of a non-elastic system that can utilize continuous rotation, such as with an electric motor, is trivial. The closed path motion can either be obtained directly by using the center of rotation as the center of a circular path, or indirectly by incorporating a crank-rocker type four-bar linkage. In an elastic system, however, obtaining a closed path requires at a minimum the use of two degrees-of-freedom, which may or may not be coupled.
More specifically, generation of a repeatable closed path in an elastic system requires at least two degrees-of-freedom that are excited at the same frequency and separated by some degree of phase lag. Obtaining a closed path in an elastic system with a single actuator therefore requires that the mechanism incorporate mechanical phase lag between two degrees of freedom. The authors initially attempted the development of a robot quadruped with a single actuator that incorporated passive mechanical phase lag to produce elliptical foot motion. Though theoretically such a system is possible, obtaining consistent foot trajectories proved difficult, due primarily to the fact that the phase in a lightly damped system is highly sensitive to any variation in the input frequency. Such behavior is a particular impediment when purposefully utilizing variation in input frequency for directional control, as is the case with the elastodynamic approach.

Upon determining that a single-actuator elastodynamic quadruped would not provide sufficiently robust performance, the authors developed an elastodynamic quadruped design based on two actuators. The phase lag required for closed path foot motion is therefore provided electronically rather than mechanically. The resulting two-actuator robot drive system, which is diagrammed in Figure 3, incorporates an inertially decoupled five-bar linkage as explained in the following section.

In designing a two degree-of-freedom revolute mechanism, one can utilize either a serial or parallel configuration. In a serial configuration, each joint is actuated relative to the previous joint, as illustrated in Figure 4. In a parallel configuration, each joint is actuated relative to a reference frame. The five-bar linkage illustrated in Figure 5 is a common implementation of a two degree-of-freedom parallel revolute mechanism.
The legs of the elastodynamic robot quadruped incorporate a parallel configuration based on a five-bar linkage rather than a serial configuration for two primary reasons. First, the base of both actuators can be attached to the same reference frame, which in turn enables all four legs of the quadruped to be actuated by the same pair of unimorph actuators. Specifically, by crossing the connecting rods shown in Figure 3, the linkage will be driven 180 degrees out of phase with respect to same set of actuators. A trot type gait requires that diagonal pairs of legs operate 180 degrees out of phase. With one connecting rod attached to each corner of each unimorph, all four legs can be driven from the same two actuators. The second significant benefit of a five-bar linkage configuration is the ability to inertially decouple the two degrees of freedom, which is of great importance when operating the mechanism near resonant frequencies.

2.2 Leg Design

The configuration of five-bar linkage shown in Figure 3 is a special configuration of a five-bar mechanism where the reference axis of rotation of links 1 and 2 are coaxially arranged. In the initial implementation of this leg configuration, elliptical foot motion was obtained quasistatically by driving the two actuators at the same amplitude and frequency, but 90 degrees out of phase. As the excitation frequency approached the dynamic regime of the mechanism, however, the linkage exhibited undesirable dynamically coupled behavior. Specifically, the mechanism demonstrated one of two fundamental modes of vibration. One of these was a symmetric mode in which the parallelogram structure would expand and contract, and one was a “rigid body” type mode in which the entire parallelogram would maintain approximately the same geometry while swinging around the grounded revolute joint. These modes are illustrated in Figure 6. Ideally, these modes would be tuned to the same frequency and occur simultaneously, but an effort to match the frequencies was
unsuccessful, since even slight differences in the resonant frequencies of the two modes would introduce the undesired behavior. This problem was addressed by utilizing the fact that a five-bar linkage can be inertially decoupled, so that the two input degrees of freedom will operate essentially independently of each other (i.e., the mechanism will behave dynamically essentially the same as it does quasistatically). Specifically, the inertial relationship between the torques about the ground reference joint of the two input links to the motion of those two links can be written as

\[
\begin{bmatrix}
\tau_1 \\
\tau_2
\end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} \\ H_{12} & H_{22} \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix}
\]

(1)

The components of the inertia tensor, \(\mathbf{H}\), are given by

\[
\begin{align*}
H_{11} &= I_1 + m_1 l_1^2 + I_3 + m_3 g_3^2 + m_4 l_1^2 \\
H_{22} &= I_4 + m_4 g_4^2 + I_2 + m_2 g_2^2 + m_3 l_2^2 \\
H_{12} &= (m_3 l_2 g_3 - m_4 l_1 g_4) \cos(\theta_2 - \theta_1)
\end{align*}
\]

(2-4)

where geometric parameters are as defined in Figure 7 and the inertial parameters are the masses and rotational inertias of each respective link. Inertial decoupling between the two links requires that the inertia tensor be diagonal, which requires that the off-diagonal element, \(H_{12}\), be zero, which requires

\[
(m_3 l_2 g_3 - m_4 l_1 g_4) = 0
\]

(5)

or

\[
\frac{m_4}{m_3} \frac{g_4}{g_3} = \frac{l_2}{l_1}
\]

(6)
Inertial decoupling is therefore achieved by selecting geometrical and inertial properties of the links to satisfy equation (6). This procedure is commonly utilized in the design of parallel robot manipulators to simplify manipulator control [10]. Implementation of an inertially-decoupled five-bar linkage as the leg structure of the quadruped eliminated the tendency of the leg to “choose” one of the two modes illustrated in Figure 6. Instead, the inertially-decoupled legs exhibited robust and repeatable elliptical foot trajectories when excited at or near resonant frequencies.

3 Robot Performance

Locomotive performance of the (power-tethered) robot was evaluated while carrying a 50-gram payload on a level surface. The payload was selected to be of approximately the same mass as the power electronics that are described in a subsequent section. The two unimorph actuators were driven with a sinusoidal voltage of ±240 volts amplitude and at the same frequency, with one actuator lagging the other by a phase of 90 degrees. Table 1 indicates the average speed of the robot quadruped operating at several different excitation frequencies, in addition to the total average power required by the actuator pair. As shown in the table, the maximum speed of the robot was 300 mm/sec at an excitation frequency of 32 Hz. The instantaneous power required by the actuators at each of the frequencies listed in Table 1 is shown for several cycles of gait in the graphs of Figures 8, 9, and 10. The fact that the average required power increases nonlinearly with speed is indicative of the increased slipping that occurs at higher frequencies between the feet and the ground surface. The authors have not yet addressed this problem, though utilizing footpads with a high coefficient of friction would most likely decrease the power required at the higher speeds.
As previously described, a significant component of the elastodynamic approach to mesoscale robot design is the dynamic control of the device (i.e., frequency based turning capability). Dynamic control of the robot was verified by demonstrating repeatable control of both right and left turns. Specifically, within the frequency region of 14 to 24 Hz, right turning was repeatedly executed in the 14-18 Hz range, with a minimum turning radius of approximately 5 cm; straight walking was achieved in the 18-19 Hz range; and, finally, left turns repeatedly occurred in the 19-24 Hz range, also with a minimum turning radius of approximately 5 cm. With the removal of the 50-gram payload, the operating ranges shifted slightly to 15-17 Hz for right turns, 17-18 Hz for straight-line motion, and 18-21 Hz for left turns.

4 Power Electronics
As mentioned in the discussion on piezoelectric actuation, the use of PZT to actuate a small-scale mobile robot requires power electronics that convert the low voltage and high current power of an electrochemical battery to the relatively high voltage and low current power required by the PZT actuator. Specifically, the full range of output for the actuators on the elastodynamic quadruped robot require $\pm 240$ volts, while a typical Lithium-type battery supplies approximately 3 volts. It should be noted that Kawahara et al. cleverly avoided the requirement of high voltages by developing multi-layered PZT bimorph actuators, though the development of such actuators is nontrivial. In addition to requiring a large electrical transmission, the power electronics must also generate a sinusoidal output, since any other type of AC output would contain multiple frequencies and thus would excite multiple modes in the robot. This would significantly impair the ability to perform frequency-based directional control and would additionally sacrifice locomotive performance. Further, the
elastodynamic quadruped required two output channels, one of which is shifted in phase by approximately 90 degrees from the other.

Figure 11 shows the power electronics circuit that was developed to drive the elastodynamic robot. This circuit incorporates a surface-mount microprocessor for pulse-width-modulated control of an H-bridge output stage, which efficiently generates a sinusoidal output. As required by the robot, the circuit generates two outputs, both sinusoids of the same amplitude and frequency, but different only in phase. The output amplitude can exceed the required 240 volts, depending on the required power, which is limited to approximately 1.25 Watts per channel. The circuit is a one-layer circuit board that measures approximately 6 cm by 9 cm and weighs approximately 37 grams. Power is provided by a lithium-manganese dioxide (NEDA-5024LC) battery that weighs approximately 16 grams and carries 700 milliamp hours of energy at 3 volts. With this combination of power electronics and battery, the total weight imposed on the robot is approximately 53 grams.

5 Self-Powered Operation

The previously described power electronics were mounted on the robot quadruped, as shown in Figure 12, and self-powered crawling was demonstrated. The battery, which is not visible in the figure, is mounted below the lower actuator in the center of the robot. The electronics presently do not incorporate a wireless link by which the excitation frequency can be controlled. In the current configuration, the frequency of excitation (and thus the direction of the robot) is set manually by adjusting a potentiometer on the board. A test was performed by adjusting the excitation frequency to approximately 15 Hz, which resulted in a right turn with a radius of approximately 25 cm. In this configuration, the robot operated for a duration
of approximately 30 minutes, which at an average speed of 150 mm/sec, corresponds to a
distance of approximately 270 meters.

6 Discussion and Conclusion

An elastodynamic design paradigm has been proposed, and the design of a mesoscale robot
quadruped based on this paradigm presented. The authors have demonstrated frequency-
based control of the robot, and have demonstrated self-powered operation. Future work
includes the implementation of a wireless control link to remotely control the frequency of
excitation, and thus the direction of the robot. Additionally, the authors wish to investigate
and implement the effects of controlling the phase imposed between the two actuators.
Specifically, the shape of the foot trajectory can be controlled by modulating the amount of
phase between the two actuators, which can be utilized to decrease forward speed and
increase foot height for rough surfaces, or conversely to increase forward speed and decrease
foot height for smooth surfaces. Finally, if the phase between the actuators is reversed
completely, the direction of motion of the robot will also reverse, providing the complete
range of forward, left, right, and backward operation of the quadruped.

Acknowledgments

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Table Captions

Table 1. Walking speed and average power corresponding to various excitation frequencies.

Figure Captions

Figure 1. Frequency response characteristics of quadruped legs for frequency-based directional control.

Figure 2. Piezoelectrically actuated elastodynamic quadruped robot.

Figure 3. Diagram of five-bar linkage-based two-actuator robot drive system.

Figure 4. Serial configuration of a two degree-of-freedom revolute joint mechanism.

Figure 5. Parallel configuration of a two degree-of-freedom revolute joint mechanism (five-bar linkage).

Figure 6. Illustration of vibrational modes in inertially coupled five-bar mechanism.

Figure 7. Definition of geometric parameters of the five-bar mechanism.

Figure 8. Instantaneous and average power for each PZT actuator at an excitation frequency of 1 Hz.

Figure 9. Instantaneous and average power for each PZT actuator at an excitation frequency of 15 Hz.

Figure 10. Instantaneous and average power for each PZT actuator at an excitation frequency of 32 Hz.

Figure 11. Power electronics circuit.

Figure 12. Power electronics mounted on robot quadruped for self-powered operation.
<table>
<thead>
<tr>
<th>Operating Frequency</th>
<th>Walking Speed</th>
<th>Average Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Hz</td>
<td>8 mm/sec</td>
<td>44 mW</td>
</tr>
<tr>
<td>15 Hz</td>
<td>150 mm/sec</td>
<td>580 mW</td>
</tr>
<tr>
<td>32 Hz</td>
<td>300 mm/sec</td>
<td>1400 mW</td>
</tr>
</tbody>
</table>

Table 1
Frequency Response of Insect Limbs

Figure 1
Figure 3

$A \sin \omega t$

$A \sin (\omega t + \phi)$

PZT 1

PZT 2

connecting rod 2

link 2

link 3

link 4 (output link)

link 1

connecting rod 1
Figure 4
Figure 5
Figure 6
Figure 7
Figure 8
Figure 9
Figure 10
Figure 12