Embedded Piezo-actuation System for Automatic Motion Control of a Fleet of Miniature Robots Operating on a Synchronized Vibrating Platform

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Abstract—**A piezo-actuation system based on a three-legged pyramidal configuration with the apex pointing upward and designed to be embedded onto miniature instrumented robots conceived for operations at the nanometer-scale is briefly introduced. The piezo-actuation system is designed to provide small increments required to position an embedded scanning probe microscope (SPM) tip within the range of the instrument. The deflection amplitude of the piezo-actuators provides the SPM tip with a dynamic range appropriate to achieve atomic resolution. The locomotion system operates at high resonant frequencies in order to achieve higher displacement speeds through a larger number of steps executed per second. To achieve high-throughput operations throughout the platform, the displacement speed of the robots become a critical issue since no SPM-based operations can be performed during travel. To provide a supplemental force, a software-controlled vibrating platform is used to increase the displacement speed of each robot. Synchronization between the piezo-actuation system of each robot and the vibrating platform is done through software interrupts generated by an embedded inertial micro-switch.**

Index Terms—**Piezo-actuators, vibrating platform, bimorph, nanorobotics, automatic control.**

I. INTRODUCTION

An embedded locomotion system for instrumented miniature robots designed to operate at the molecular scale must be capable of fast displacements between two successive locations while being accurate enough to position each robot within the range of the embedded instrument. Since no useful work is being performed at the nanoscale during travel, the design of a locomotion mechanism must be capable of fast motion while retaining the capability of positioning each instrumented untethered robot with enough accuracy. Fast displacements also contribute to increase the overall throughput or number of operations performed at the nanoscale per second within the same platform.

Piezo-ceramic actuators have been intensively used in the recent years in high precision translation systems and in precise robotic applications, particularly at the nanometer-scale. The small deflection amplitudes and the high resonant frequencies of piezo-ceramic actuators allow fast displacements with small step sizes required in our particular applications.

In our previous implementations, each robot named NanoWalker [1-2] relied on three embedded piezo-ceramic actuators in a tubular form to travel across the platform. The three piezo-tube actuators embedded in each robot were mounted in a pyramidal fashion with the apex pointing upward allowing faster locomotion speeds compared to previous methods. The overall size of the previous version of the NanoWalker was (~ 32 mm × 32 mm × 30 mm) where most of the volume was occupied by three DC/DC converters required to provide the high actuation voltage signals to the piezo-actuators. Minimizing the overall size of each instrumented robots would translate into a higher density of instruments per platform and hence potentially increasing the throughput of operations performed at the molecular-scale.

In an attempt to decrease the overall size of each robot, a second version of the NanoWalker robots with a new embedded actuation system is proposed. Since the new actuation system would in a worst case, requires only one DC/DC converter and the fact that the same piezo-actuators are also used to control the movement of an embedded scanning probe microscope (SPM) tip, the overall dimensions of each robot could be reduced significantly. To increase the displacement speed of this new version of the NanoWalker robots, a software-controlled automatic vibrating platform is also designed to provide additional vertical force during motion. Synchronization is ensured by a special inertial micro-switch embedded in each robot.

II. ACTUATION SYSTEM

As depicted in Fig. 1, the actuation system is comprised of the piezo-actuators embedded onto each robot and a vibrating platform providing an additional vertical force to all robots to achieve faster displacement speeds. For smaller steps required for accurate positioning, the platform is designed to vibrate at a frequency approaching the resonant frequency of each robot characterized at ~ 4.4 kHz for the initial design. For the initial displacement between two locations further apart, the accuracy in displacement can be reduced and faster displacements can be achieved through larger bouncing steps. In such a case, the vibrating frequency of the platform will be lowered to accommodate the time of flight during motion.

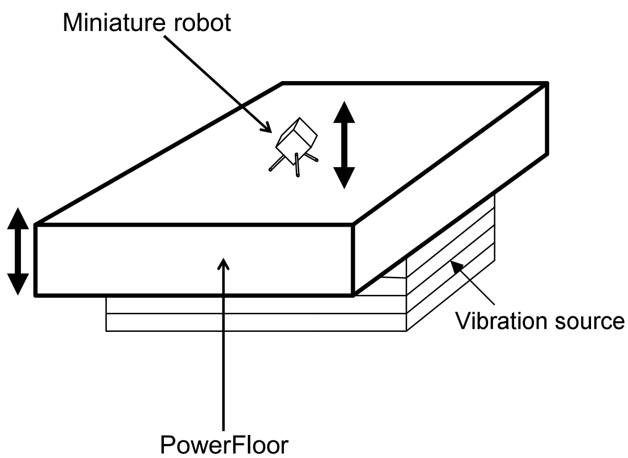

Fig. 1 Principle of the vibrating platform

To reduce further the overall size of each robot, power is provided from an external source through the legs of the robots when in contact with a special floor referred to as "PowerFloor" as depicted in Fig. 1, a principle further explained in [3].

Each leg of the robot consists of a two-layer piezoelectric bimorph configured in parallel mode as shown in Fig. 2. The extremity of the leg in contact with the floor is made of a conducting material such as steel to deliver the power between the surface and the embedded electronics.

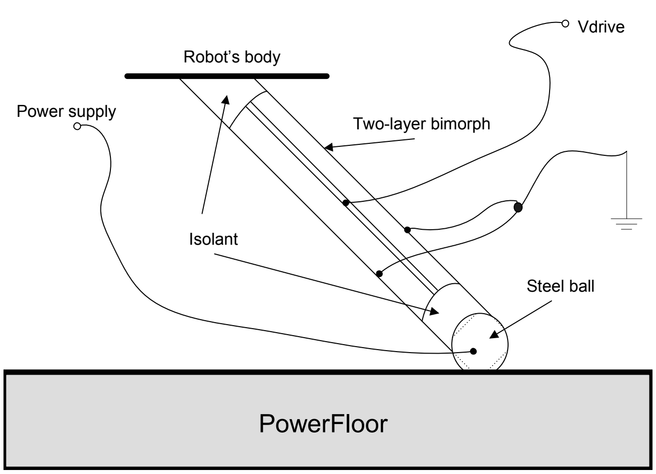

Fig. 2 Schematic of one actuating leg

The actuation system embedded onto each robot is based on a three-legged pyramidal architecture with the apex pointing upward. Each leg is a two-layer ceramic bender (bimorph) actuator where several parameters such as the amplitude and the rate of deflection are controlled by sophisticated algorithms executed through complex onboard electronics. The three-legged architecture provides the minimum implementation for static stability of the structure and minimizes the amount of electronics and power required for motion control. Unlike terrestrial insects that makes use of alternating triangles of support during walking and running (as illustrated in Fig. 3), this new version as for the preceding implementation of the NanoWalker robot, relies on a single triangle of support during motion.

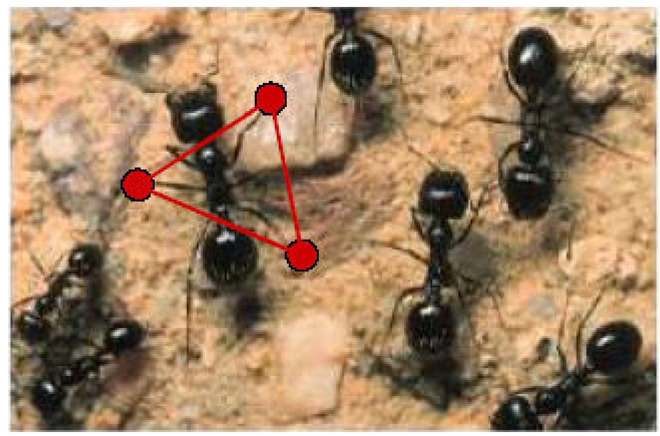

Fig. 3 Motion of ants with triangle of support

For symmetry, an angle of 120^o separates horizontally each pair of legs as depicted in Fig. 4a allowing each actuator to act as the front leg while optimizing rotational displacements. The legs are fixed to the body of each robot with an angle of 45^o with respect to the surface (Fig. 4b) in order to optimize both vertical and horizontal force vectors.

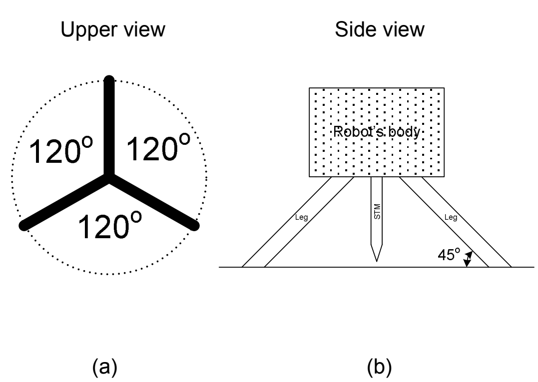

Fig. 4 Geometry of the actuation system embedded in each robot, (a) upper view and (b) side view

III. Main Characteristics of the Embedded Actuation System

Assuming that the weight of the robot is distributed evenly among the three legs, the force F of each leg necessary to lift the robot from the surface of the platform is

$$F > \frac{m\,g}{3} \cdot \quad (1)$$

In Eq. 1, m and g are the mass of the robot and the gravitational acceleration respectively. The next version of the robot is estimated to have a total mass of approximately 10-15 grams.

The minimum deflection increment of the legs is dictated by the embedded 16-bit D/A converter and must be sufficiently small to support scanning operations at the atomic scale. For carbon atoms for instance (also considered in our present version of atomic-scale positioning method where position is determined by counting carbon atoms using the embedded SPM), at least 10 readings per atomic lattice (< 0.3 nanometer (nm)) as illustrated in Fig. 5 would be performed, limiting the overall scan region when the robot is stable to approximately ± 600 nm.

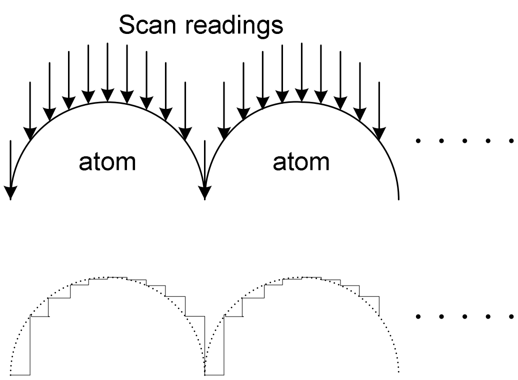

Fig. 5 Scanning operations at the atomic scale

A two-layer parallel-operation bimorph has been chosen because it offers several advantages. First, for the same motion, a two-layer element poled for parallel operation needs only half the voltage required for series operations [4], reducing the power requirement by half. Second, by connecting the two outer electrodes to ground, two-way deflections can be controlled using only the middle electrode. This means that the amount of embedded electronics can be significantly reduced (at least by half), leading to a greater level of minimization.

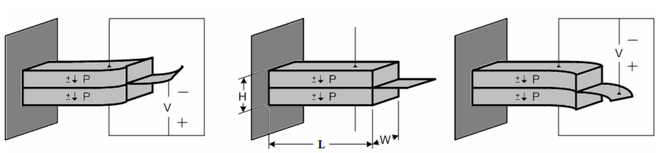

Fig. 6 Two-layer bending element poled for parallel operation (from [4]).

The deflection X of a bimorph operating in parallel mode resulted from a driving voltage V is computed as

$$X \le 3\, d_{31} \frac{L^2}{H^2} V \cdot \quad (2)$$

As depicted in Eq. 2, for a specific piezo-material and a given voltage amplitude which for a required power density is limited when embedded in a miniature robot, the deflection depends on the ratio between the length of the piezo-leg which is also constrained by the size of the robot and the thickness of the bimorph.

The resulting force F from a given deflection X on a bending element (cantilever) is determined as

$$F = \frac{1}{4} Y \frac{W\,H^3}{L^3} X \cdot \quad (3)$$

The blocked force F resulting from the drive voltage V is

$$F = 0.75\, Y\, d_{31} \frac{W\,H}{L} V \cdot \quad (4)$$

The force is then inversely proportional to the length of the bimorph while improved with an increased width and thickness of the bimorph which as the voltage amplitude, are limited by the overall dimensions of the robot. Furthermore, the resonant frequency F_R of the robot's actuators must be sufficiently high allowing the robot to reach its working area in a minimum amount of time. The resonant frequency of a bimorph operating in parallel mode is computed as

$$F_R = 0.16 \frac{H}{L^2} \sqrt{\frac{Y}{\rho}} \cdot \quad (5)$$

We recall that In Eqs. 2-5, L, W, H are the dimensions of the bimorph in terms of length, width, and thickness, while d_{31}, Y and ρ are the piezoelectric strain constant, the Young's modulus and the density of the material respectively. Notice that the resonant frequency of a bimorph operating in parallel mode does not depend on its width.

Another concern is the capacitance of the electrodes in the bimorph. To achieve a higher level of miniaturization and to lower the requirement in power density which is limited by the embedded electronics especially at high resonant frequencies, the capacitance must be as small as possible. The piezoelectric capacitance C of a bimorph operating in parallel mode is computed from the following relationship

$$C = 2\, K_T\, \varepsilon_0 \frac{W\,L}{H}. \quad (6)$$

In Eq. 6, K_T is the relative dielectric constant of the piezo-material and ε_0 is the vacuum permittivity (ε_0 = 8.854 x 10^{-12} Farad/meter). Therefore, the length of the bimorph must be lowered and the thickness must be increased, providing higher actuation force.

IV. Actuation Modes

The two basic actuation modes are: 1. displacement or locomotion, and 2. scanning. The basic principle of locomotion is illustrated in the simple schematic depicted in

Fig. 7 where the force applied by each leg is adjusted according to the desired direction of motion including rotation.

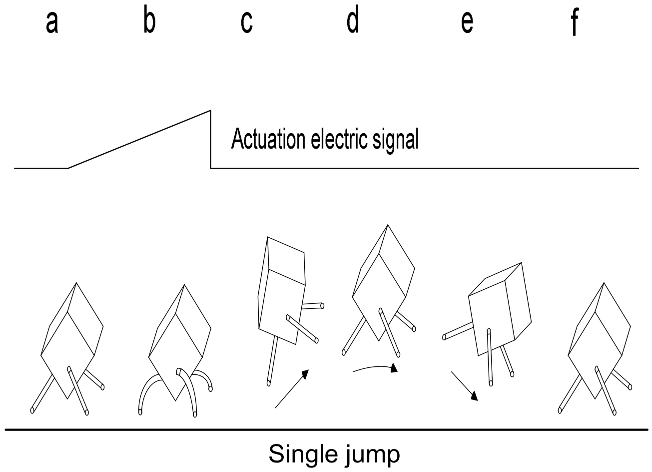

Fig. 7 Basic principle of locomotion, a. initial position, b. combined forces from the legs and the floor, c. robot is lifted, d. robot loosing contact with the floor, e. robot is falling down, f. robot is back on the floor. The deflection amplitudes of the legs are exaggerated here for clarity.

The scanning operation is performed by bending the legs with appropriate amplitudes so that the tip of the instrument can move around the surface to be scanned as depicted by the simplified diagrams in Fig. 8.

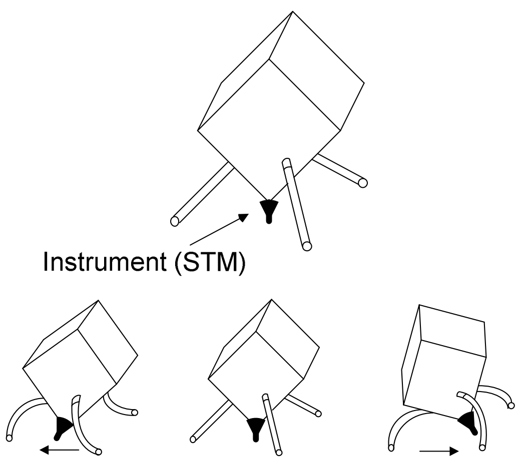

Fig. 8 Simplified schematics showing the scanning operations. Again, the amplitudes of defection of the legs have been exaggerated here for clarity.

V. Driving Harware

Amplitude modulation is used to drive the piezo-actuators. The circuit required for amplitude modulation consists of a 16-bit D/A converter (DAC) and a linear operational amplifier as illustrated in the simple schematic in Fig. 9. The DC/DC converter depicted in Fig. 9 converts a +5 VDC (supplied through the floor) to ± 48 VDC required to drive the bimorphs. The resolution of the DAC is also selected to provide an adequate dynamic range for scanning purposes.

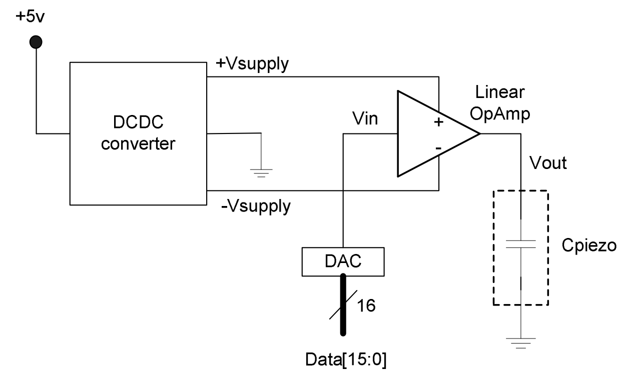

Fig. 9 Simplified block diagram showing the main driving circuit

VI. Conclusions

A new actuation mechanism for a fleet of miniature instrumented robots designed to interact at the nanometer-scale has been briefly introduced. The location method uses a combination of embedded bimorph actuators based on a three-legged architecture that can be supplemented by a software-controlled vibrating platform to achieve higher displacement speeds. The piezo-actuation system embedded in each robot is also designed to provide scanning capability at the atomic-scale. Although the proposed actuation system has great potentials for such high-performance platform, the conception of an adequate control strategy and automatism remains a critical issue for the success of this method.

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