Miniaturization of a Piezo-Actuation System Embedded in an Instrumented Autonomous Robot

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***Abstract*— The paper introduces a miniaturization approach for the piezo-actuation and related systems embedded in a new version of a miniature autonomous robot named NanoWalker for operations at the molecular scale. Since the throughput of such platform is determined in great part not only by the number of robots operating simultaneously but also by the density of robots, a higher level of miniaturization would typically translate into a higher number of operations performed per second. First estimations suggest that the initial overall dimensions of 30 mm^3 of the preceding version of the NanoWalker can be reduced to less than 10 mm^3 for the future prototype of the robot.**

***Index Terms*—Miniaturization, nanorobotics, piezo-actuator, bimorph actuator.**

I. Introduction

In recent years, developments in the fields of nano-sciences and nano-engineering have had a great impact on the methods used to manufacture products [1]. Active research is underway to develop new techniques for molecular assemblers, paving the way for a wide variety of applications ranging from biology and medicine to precision engineering. This led to the requirement for automation where miniature robots capable to operate at the micrometer and nanometer scales have been emerging as a new area. These robots would enable new tools and novel approaches to design, construct, and control micrometer and nanometer-scale systems. Towards this trend, molecular manufacturing could allow precise control of the assembly process down to the molecular level. New commercial opportunities will emerge and high-throughput automation will be required as one of the key issues for the successful implementation of factories operating at the nanoscale, often referred to as nano-factories.

In [1], the NanoWalker project proposed a high-throughput nano-factory in the form of a fleet of miniature wireless instrumented robots. The wireless implementation of these robots allows them to operate on the same platform with a high degree of freedom. On the other hand, their miniaturization allows more robots to operate simultaneously within the same area, hence increasing the throughput rate on each platform. Thus, miniaturization is a key requirement to achieve higher throughput for such type of platform. However, miniaturization has serious impacts on every aspects of the development of the robots, including but not limited to both the mechanical and electronic design. For instance, as the size of the robot decreases, the length of the piezo-actuator of the robot decreases as well resulting in a reduction in the deflection and stretching amplitudes of the piezo-actuator [2]. While this can be compensated with a higher voltage level, the size of the robot increases due to the use of DC/DC converters needed to convert the relatively low supply voltage levels of the embedded computer to the high actuation voltage level of the piezo-actuators. Thus, miniaturization is a real challenge and in the case of the NanoWalker, it represents a must-be-solved problem.

Miniaturization does not consist of simple use of small-size components. Serious considerations must be taken into several elements of the robots, including but not limited to its geometry, structure, as well as its piezo-electro-mechanical actuation system. For instance, the actuation architecture of the previous version of the NanoWalker robot reduced its size by relying on only three legs providing the minimum number of contact points to guarantee static stability of the structure while minimizing the drive electronics and voltage conversion circuitries required for actuation [2]. However, with the use of the piezoelectric tube as actuation element, it was not possible to achieve further miniaturization in the previous version of the NanoWalker robot. In this paper, a miniaturization approach is proposed to be applied to the development of the future actuation system of the NanoWalker robot.

Bimorphs are presently used to replace the piezoelectric tube allowing a reduction in the number of electrodes to be driven from 16 to 3. Moreover, although the same three-legged architecture is used in the new version of the robot, it becomes possible to eliminate completely the piezoelectric tube needed to derive the movement of the Scanning Tunneling Microscopy (STM) tip [3] by making use of the deflection of the piezo-actuated legs of the robot.

II. Overview of the Previous Actuation System

The NanoWalker robot is a high-precision wireless instrumented three-legged miniature robot designed for operations at the nanometer scale. Unlike a laboratory robot

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that might move samples from one instrument to another, the NanoWalker robot is designed to function as a mobile scientific instrument [4]. Its name is due to its capacity of locomotion in the nanometer range.

To appreciate the benefits of the miniaturization approach proposed in this paper, this section presents an overview of the piezo-actuated system implemented for the previous version of the NanoWalker robot which measures approximately 30 mm^3. A diagram of this implementation is depicted in Fig. 1. As shown, the basic structure of the robot consisted of the platform body mounted on three legs made of piezo-ceramic tubes. An instrument, such as a STM, can be installed in the middle of the platform to perform the task assigned to the robot through interactions at the nanometer-scale.

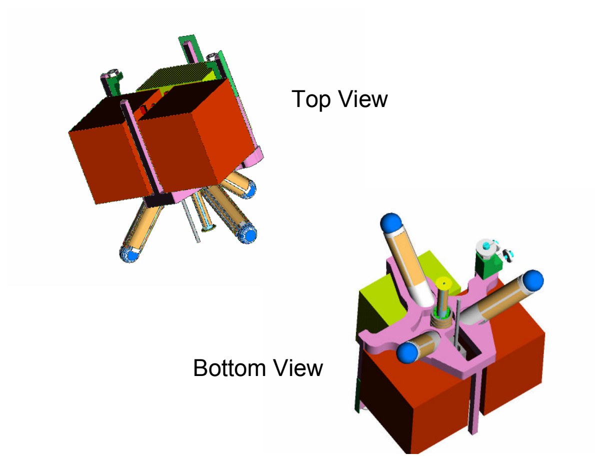

Fig. 1 The NanoWalker robot with its three-leg piezoelectric actuators (embedded electronics not shown). The DC/DC converters required for voltage conversions are shown as large blocks.

As for the previous version, the piezo-locomotion system of the new version of the NanoWalker relies on a three-legged architecture formed as a triangle with the apex pointing upward. The legs are separated by an angle of 120 degrees from each others on the horizontal plane and an angle of 45 degrees vertically or with respect to the surface. This architecture guarantees minimum implementation for static stability of the structure and as a result, it reduces the amount of electronics and power required for motion drive and control.

In the previous implementation, each leg as well as the actuator used to scan the surface with the embedded STM consisted of a piezoelectric tube. Deflections of these actuators are achieved by applying voltages to quadrant electrodes as shown in Fig. 2. This configuration of the electrodes enables different motions by proper deflections and coordination among each leg. To perform large deflections, a relatively high voltage level of ±150 volts was required, which posed serious constraints on miniaturization mainly due to the unavoidable presence of the DC/DC converters.

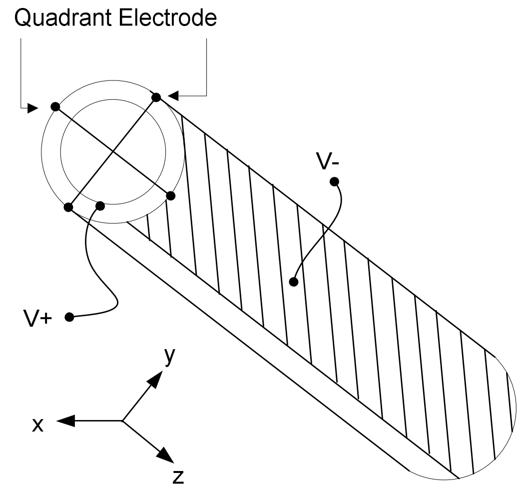

Fig. 2 Diagram of a piezoelectric tube used to implement the leg.

III. Miniaturization Approach

The approach presented here proposes several steps to achieve further miniaturization in the development of the actuation system of the NanoWalker robot, they are summarized in the following sections.

A. Geometry to Minimize Space

As shown in Fig. 3, the three legs of the robot are fixed on the three lower faces of a cube allowing all electronic components (dies, resistors, etc.) to be put on the three upper faces. The instrument carried by the robot is placed underneath at the center of the body, achieving symmetry and stability at the same time.

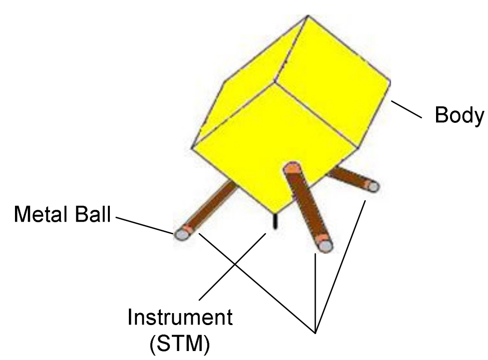

Fig. 3 Geometry of the new NanoWalker robot

B. Actuation Mechanism to Reduce Control Elements

The choice of the actuation mechanism has a non-negligible impact on the miniaturization. The previous actuation system of the NanoWalker relied on the use of piezoelectric tube configured as shown in Fig. 2. Although requirements for precision and displacement speed might be met using this type of actuator, it was not possible to reduce further the size of the robot due to the complexity of the driving hardware to control the 16 electrodes of the 4 piezo-tubes (4 electrodes on each tube, 3 tubes for the 3 legs and 1 tube for the STM) as well as the large size of the 3 DC/DC converters needed to supply the power to the piezo-tubes.

On the other hand, the two-layer parallel-mode version of the bimorph actuator depicted in Fig. 4 can meet the requirements set for the NanoWalker robot in terms of precision and displacement speed while suiting well to miniaturization.

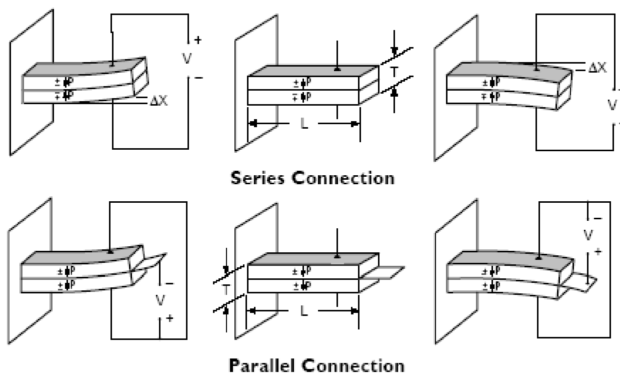

Fig. 4 Two-layer bending element in two modes of operation [from 5].

First, for the same motion, a two-layer element poled for parallel operation needs only half the voltage required for series operations reducing the power requirements by half. Second, by connecting the two outer electrodes to ground, two-way deflections can be controlled using only the middle electrode (see the parallel connection depicted in Fig. 4). This means that the number of electronic parts is significantly reduced, at least by half, providing a greater level of miniaturization. Moreover, the deflection of each leg will be controlled by only one electrode while there will be no need to use any piezo-element to control the STM following the scanning mode shown in Fig. 5 [6].

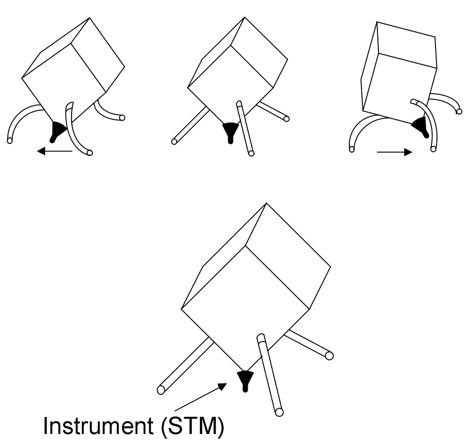

Fig. 5 STM and scanning operations

C. Architecture to Reduce Mechanical Structure

The new design can eliminate the need for the piezoelectric tube to control the scanning of the STM by bending the legs in appropriate amplitudes so that the tip of the instrument can move around the surface to be scanned as shown in Fig. 5. Although this technique does not offer a scanning control as flexible as the previous configuration based on a dedicated piezoelectric tube, the importance of miniaturization makes it a worthy trade-off.

D. Avoidance of DC/DC Converters through Technologies using Similar Voltage Levels

The high voltage level required to drive the piezoelectric tubes in the previous version of the NanoWalker represents the main constraint for further miniaturization. Relatively large DC/DC converters were required to convert the low voltage level used by the on-board electronic components (e.g. on-board computer) to a higher voltage level (±150 V) to drive the piezo-actuators, as shown in Fig. 6. For instance, it can be shown that for a 5A-type ceramic bimorph of 7.35 mm long, 0.508 mm wide, and 0.508 mm thick, a driving voltage as low as 5 volts, the same voltage provided to drive the on-board electronics, can be used. Thus, the use of DC/DC converters can be completely avoided, resulting in a substantial reduction of the overall size of the robot.

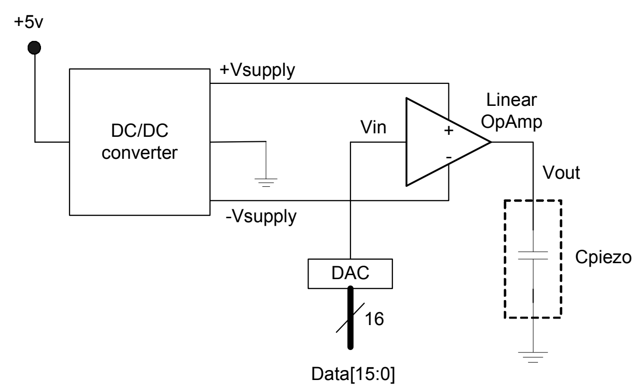

Fig. 6 Simplified block diagram of the main driving circuit of the STM piezo-actuation element.

E. Use of External Additional Actuation Force

The blocked force F of a bimorph resulted from a driving voltage V is given as

$$F = 0.75\, Y\, d_{31} \frac{W\,H}{L} V \cdot \qquad (1)$$

In Eq. 1, L, W, H are the dimensions of the bimorph in terms of length, width, and thickness, while d_{31} and Y are the piezoelectric strain constant and the Young's modulus of the material respectively.

Eq. 1 implies that a reduction of the driving voltage due to miniaturization will come along with a reduction of the actuation force. Therefore, in order to maintain miniaturization, additional force required for the locomotion of the robot must be provided from an external source. Such source in the proposed implementation takes the form of a vibrating platform providing supplemental vertical forces [6]. A simple diagram of such vibrating platform is depicted in Fig. 7.

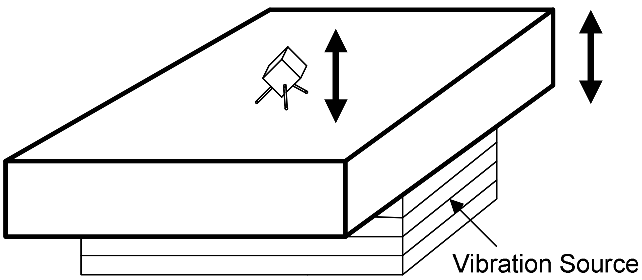

Fig. 7 Proposed vibrating platform

RESULTS AND CONCLUSION

The estimated results are presented in Table 1.

TABLE 1
Specifications of the bimorph.

L = 7.35 mm, W = 0.508 mm, H = 0.508 mm					
X (μm)	V (volts)	Fr (kHz)	C (nF)	F (N)	I (μA)
0.6	5	4.4	0.2	0.002	5

m	mass of the robot	(grams)	10 g
ε_0	vacuum permittivity	(F/m)	8.854×10^{-12}
g	gravitational constant	(m/s^2)	10
Y	Young modulus	(N/m^2)	6.6×10^{10}
d_{31}	piezoelectric strain constant	(m/V)	190×10^{-12}
K_T	relative dielectric constant	(unitless)	1800
ρ	density	(kg/m^3)	7800
L	length	(m)	
W	width	(m)	
H	thickness	(m)	
F	force	(N)	
X	bender deflection	(m)	
F_R	resonant frequency	(Hz)	
V	driving voltage	(V)	
C	piezoelectric capacitance	(F)	

The force generated by one bimorph actuator or a single leg for the new version of the robot is estimated at 0.002 Newton (N) causing a deflection of 0.6 μm in each direction (total amplitude of 1.2 μm) with a resonance frequency of 4.4 kHz. Hence, the vibrating platform must provide a maximum vertical force of 0.09 Newton for an estimated total mass of 10 grams per robot to eliminate the gravitational force but not to cause any movement of the robots, allowing 0.002 Newton per leg or piezo-actuator for directional displacement on the horizontal plane.

ACKNOWLEDGMENT

This work is presently supported in part by a Canada Research Chair (CRC) in Micro/Nanosystem Development, Construction and Validation, the Canada Foundation for Innovation (CFI), the Natural Sciences and Engineering Research Council of Canada (NSERC), and the Government of Québec.

REFERENCES

[1] S. Martel and I. Hunter, "Nanofactories based on a fleet of scientific instrument configured as miniature autonomous robots," *Journal of Micromechatronics*, vol. 2, no. 3-4, pp. 201-214, 2004.

[2] S. Martel, "Fundamental principles and issues of high-speed piezoactuated three-legged motion for miniature robots designed for nanometer-scale operations," *The International Journal of Robotics Research*, vol. 24, no. 7, July 2005.

[3] C. Chen, *Introduction to scanning tunneling microscopy*, Oxford University Press, New York, 412 pages, 1993.

[4] S. Martel, P. Madden, L. Sosnowski, I. Hunter, and S. Lafontaine, "NanoWalker: a fully automomous highly integrated miniature robot for nano-scale measurements," *Proceedings of the European Optical Society (EOS) and SPIE International Symposium on Envirosense, Microsystems Metrology and Inspection*, vol. 3825, June 14-18, 1999.

[5] Piezo Systems, Inc., http://www.piezo.com/catalog.html, 2005.

[6] A. T. Nguyen and S. Martel, "Embedded Piezo-Actuation System for Automatic Motion Control of a Fleet of Miniature Robots Operating on a Synchronized Vibrating Platform," *The 6th World Congress on Intelligent Control and Automation*, July 16-20, 2006.