Locomotion of a Miniature Robot Based on Synchronized Vibrating Actuation Mechanisms

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***Abstract*—A new principle for controlled motion of microrobots is briefly described. A controlled vibrating floor allows further miniaturization of each robot by providing additional vertical force to compensate for a reduction of the force available on the three piezo-ceramic legs of each robot due to space constraints. Displacement is only achieved when a miniature robot activates its piezo-legs providing the additional required lift for controlled directional motion. Preliminary experimental data show that such a platform is already capable to perform displacements. Our first prototypes demonstrated a maximum displacement rate of 1.7 mm/s when the robot moved by itself using its three legs and 14 mm/s when the robot is being assisted by the vibrating surface.**

***Index Terms*—Microrobots, vibrating platform, piezo-actuator.**

I. INTRODUCTION

THE conception of an embedded locomotion system to allow a fleet of instrumented miniature robots designed for interactions at the molecular scale is critical. In order to increase the overall throughput or number of operations performed per second within a same platform, each robot must be miniaturized. To achieve further miniaturization, a new embedded locomotion is proposed. Such locomotion system must be able of fast displacements between two successive locations while being sufficiently accurate to position each robot within the range of an embedded instrument, typically within a few tenths of nanometers (nm) if implemented for a nanofactory [1]. Such locomotion system is intended to be embedded on the NanoWalker-2 robot that follows the step of the previous NanoWalker platform [2] which aimed at minimizing the overall size of each instrumented robot in order to achieve a higher density of instruments and hence potentially increasing the throughput of operations per platform [3]. Fig. 1 shows a basic diagram of the proposed platform which is composed of a fleet of untethered miniature robots capable of carrying instruments such as a Scanning Tunneling Microscope (STM).

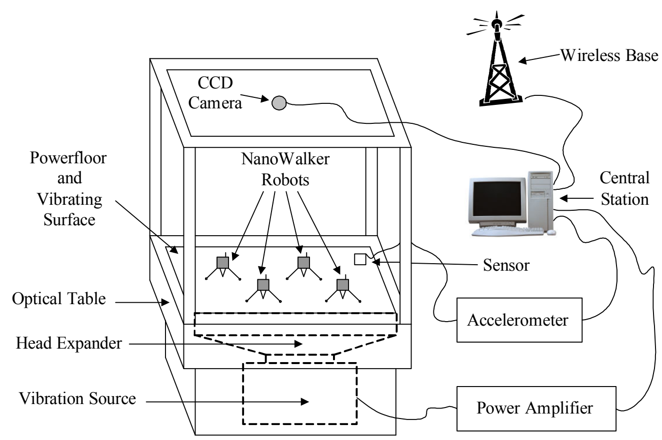

Fig. 1. Basic diagram of miniature robots NanoWalker-2 platform.

Interactions between the users and the platform are communicated through a Graphical User Interface (GUI) displayed on a central control station which supervises the global task by passing special commands, instructions, and data to and from the robots using RF communication links. Presently, the position and the displacement of each robot are tracked by a global CCD camera-based positioning system. In an attempt to increase the throughput of the second version of the NanoWalker platform, a new locomotion system based on software-controlled automatic vibrating mechanisms is being developed. As described in [4], vibration motors have been embedded directly on the microrobots as actuation mechanisms. Due to the miniaturization of the new NanoWalker robot, an external vibrating surface is synchronized with each "jumping" step of the piezo-actuated three-legged robot to provide additional force during motion in order to accelerate the displacement speed of the robot.

II. ACTUATION SYSTEM

As depicted in Fig. 2, the actuation system is comprised of two synchronized vibrating mechanisms: the piezo-actuators embedded onto each robot and a vibrating surface. The synchronization between these two mechanisms is achieved through the generations of software interrupts to a processor from an inertial switch embedded in each robot [5].

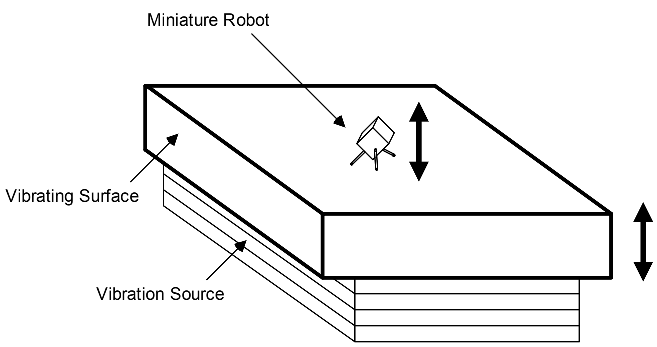

Fig. 2. Basic diagram of the vibrating platform.

A. Piezo-actuators

As for the first version of the NanoWalker robot, the actuation system embedded onto each robot is based on a three-legged pyramidal architecture with the apex pointing upward [2]. 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 that will be executed through complex onboard electronics [3] when the untethered version of the robot will be completed. Fig. 3 depicts an experimental prototype of the new NanoWalker robot where the embedded three-legged piezo-actuators are shown.

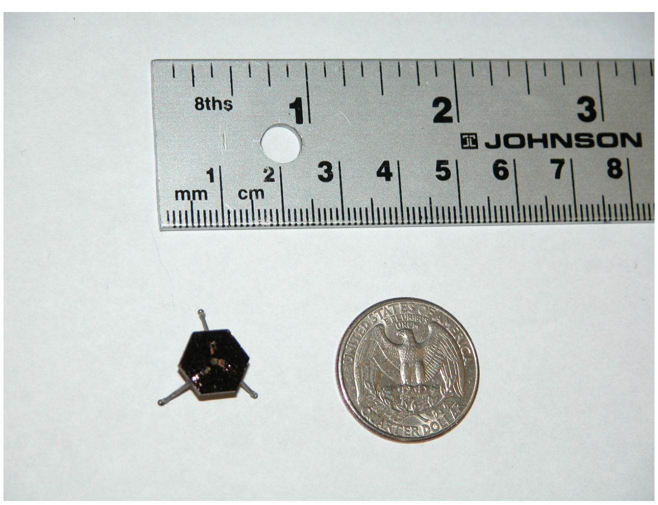

Fig. 3. A prototype of the new NanoWalker robot.

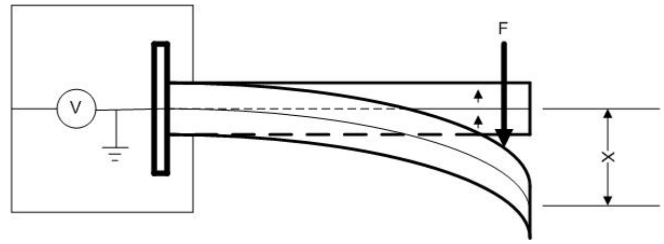

Fig. 4 Two-layer parallel-mode bimorph.

The deflection X of a bimorph operating in parallel mode from a driving voltage V (Fig. 4) is computed as

$$X \leq 3\, d_{31} \frac{L^2}{H^2} V \cdot \qquad (1)$$

The blocked force F resulting from the drive voltage V is

$$F = 0.75\, Y\, d_{31} \frac{W\, H}{L} V \cdot \qquad (2)$$

The resonant frequency F_R of a bimorph operating in parallel mode is computed as

$$F_R = 0.16 \frac{H}{L^2} \sqrt{\frac{Y}{\rho}} \cdot \qquad (3)$$

In Eqs. 1-3, 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. The basic principle of locomotion is illustrated in the simple schematic depicted in Fig. 5.

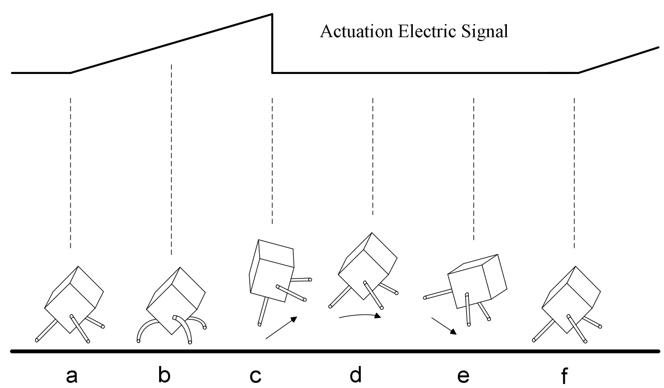

Fig. 5. Basic principle of locomotion; a. initial position; b. combined forces from the legs and the floor; c. robot is lifted, d. robot loosing contact with the floor, e. robot is falling down, f. robot is back on the floor.

B. Vibrating surface

Eq. 2 implies that a reduction of the driving voltage due to miniaturization comes along with a reduction of the actuation force. Therefore, in order to maintain miniaturization, supplemental force required for locomotion of the robot must be provided from an external source. Such source takes the form of a vibrating surface in our particular implementation.

Fig. 6 shows our experimental setup in which the vibrating surface is excited by a shaker (DP-V11 - Data Physics Corporation) through a homemade head expander. A closed-loop control block diagram of the platform is shown in Fig. 7. Due to the required precise positioning of the robots, a silicon wafer mounted on a special platform (Fig. 8) has been used for the floor since flatness and inclination of the surface are critical.

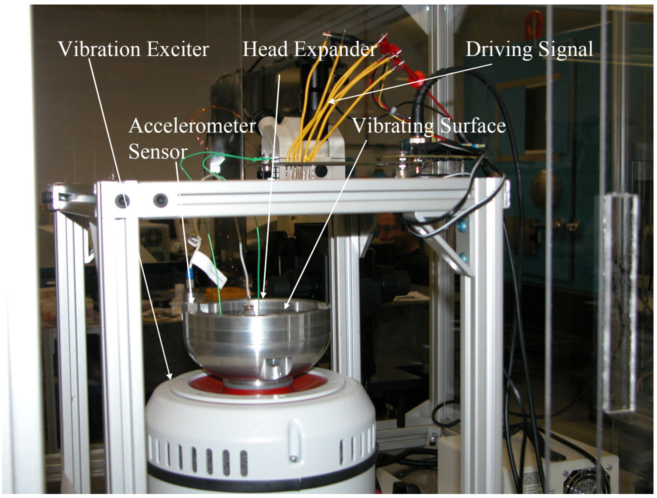

Fig. 6. Experimental setup of the vibrating platform.

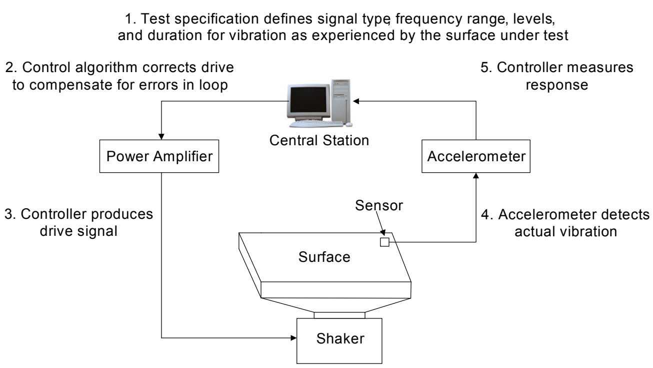

Fig. 7. Closed-loop control of the vibrating platform.

Data recorded from an accelerometer fixed to the vibrating surface are fed to a computer for generating the proper feedback response providing through a power amplifier, the required vibration level and frequency to the vibrating surface. Due to the required precise positioning of the robots, the selection of the vibration exciter (shaker) must have vertical displacement with minimum horizontal motion, and high resolution in the control of the displacement, force, and frequency to allow fine-tuning of the synchronization between the piezo-actuators of the robot and the vibrating surface.

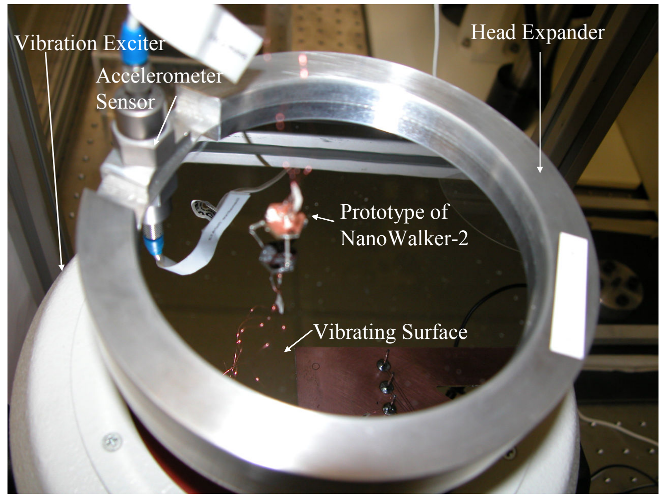

Fig. 8. Surface of the vibrating platform with a prototype of the new NanoWalker robot.

The design and fabrication of the head expander is complex and is beyond the scope of this paper. Nonetheless, some design principles are briefly introduced. The head expander must be machined with great care in such a way that the vibration is uniformly transmitted from the armature of the shaker to the vibrating surface to the required levels and frequencies. A well designed head expander must be as light as possible, very rigid, highly damped, and with a transmissibility approaching 1 within the desired frequency range [6]. The choices of materials used to make the head expander include magnesium alloys such as AZ31B and aluminum alloys such as 6061-T6 [7]. The geometry of the head expander must be well architected so that wave propagations on the vibrating surface are well and evenly distributed.

III. Basic Principles Behind the Proposed Locomotion

As driving voltage of the piezo-actuators of the robot is significantly reduced due to match the operating voltage of the on-board electronics in order to avoid voltage converters that contribute to increase the size of the robots, the resulting force would not be sufficient to lift the robot off the surface due to gravitation. In order to counterbalance this force, the vibrating surface provides additional vertical force in such a way that zero-gravity can be reached allowing the robot to travel faster with less force embedded on the each robot. Therefore, minimum force provided by the piezo-actuators is required to achieve motion. However, such a condition can be obtained only when the vibrating surface is in perfect synchronization with the bouncing movement produced by the piezo-actuators of the robot. Fig. 9 depicts the principle behind this new locomotion system.

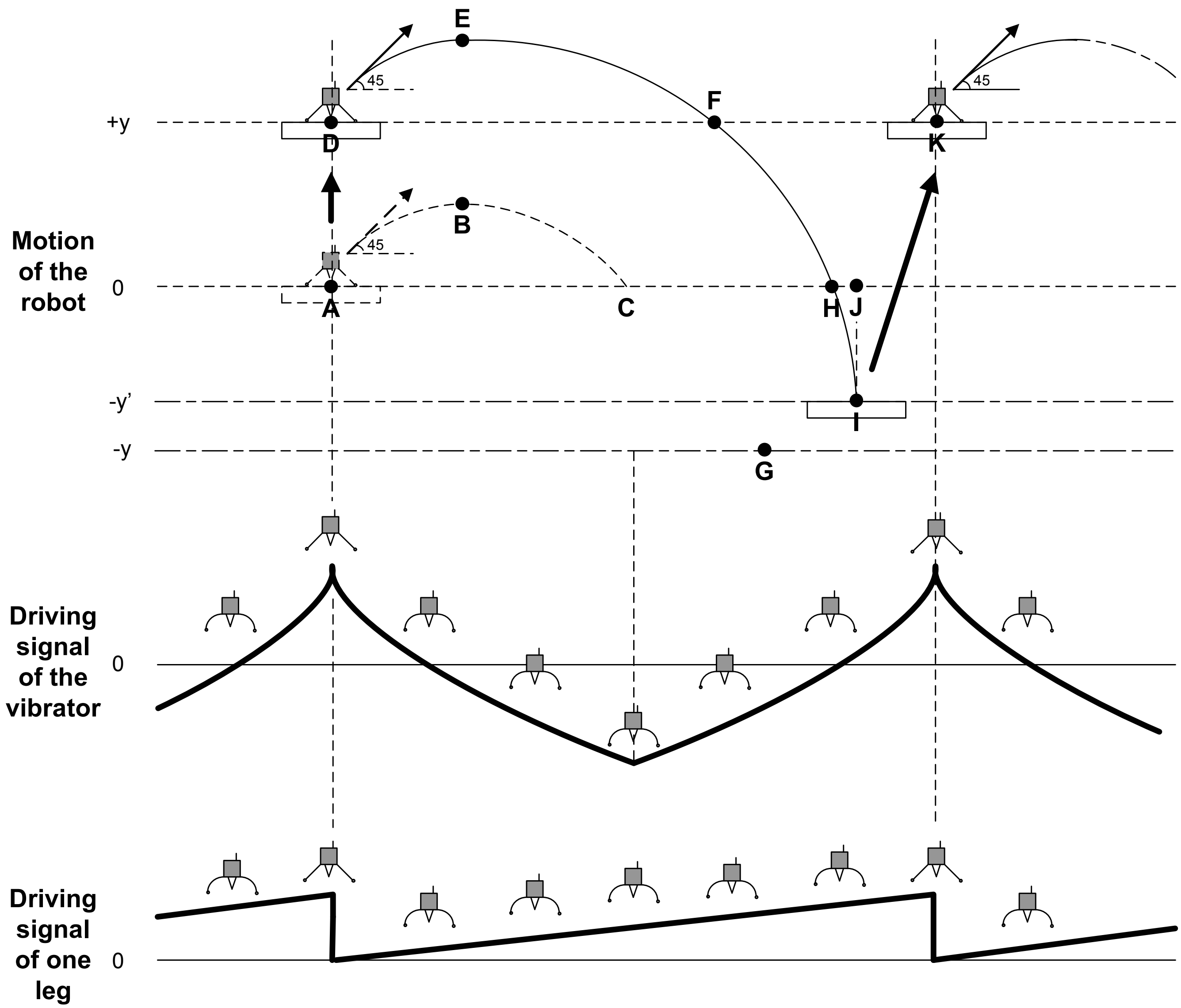

Fig. 9. Motion principle of the synchronized vibrating actuation system.

A. Driving the piezo-actuators embedded on each robot

A saw-tooth voltage signal (Fig. 9) is used to drive the piezo-actuators embedded onto each robot. A blocking force is gradually accumulated in each piezo-actuator until the vibrating surface reaches its maximum (at *D*). At this instant, all the accumulated force of the piezo-actuators is then quickly released producing a thrust to push the robot upward.

B. Driving the vibrating exciter

The second Newton law requires an acceleration a to produce a force F on an object of mass m as formulated in Eq. 4. To counterbalance gravitation, a must be constant along the course of each displacement direction of the shaker. Therefore, a can be produced simply by a square wave as in Fig. 10a.

$$F(t) = ma(t). \tag{4}$$

The velocity v can be seen as the result of the acceleration a of an object during a period of time dt as stated in Eq. 5. Therefore, the waveform of v can be found by inspection as shown in Fig. 10b.

$$v(t) = \int_{t1}^{t2} a(t)\,dt = a(t)\,t + C \tag{5}$$
$$\textit{where } C \textit{ is an initial velocity}$$

The displacement y resulted from an object traveling with an acceleration a is computed from Eq. 6. Hence, the waveform of y can be found by inspection as shown in Fig. 10c.

$$y(t) = \int_{t_1}^{t_2} v(t)\,dt = \frac{1}{2}a(t)\,t^2 + Ct + D \tag{6}$$
$$\textit{where } C \textit{ is an initial velocity}$$
$$\textit{and } D \textit{ is an initial displacement}$$

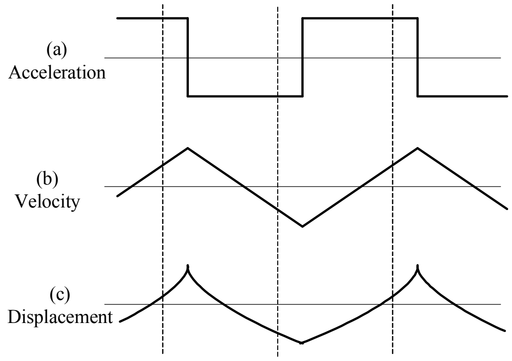

Fig. 10. Driving signal of the vibrating exciter (shaker).

C. Synchronization of the vibrating mechanisms

In order to maximize the displacement speed of the robot using the proposed vibrating system, the vibrating surface must be perfectly synchronized to the jumping steps of the robot. This synchronization constitutes a critical element in the locomotion system of the entire robot platform. It must be accomplished in such a way that only the actuated robots will move to their next location while the non actuated ones will remain on the spot. In such a system, the vibrating surface plays the role of a force motor while the legs of the robot acts as a direction guidance mechanism. Fig. 9 depicts the principle of such synchronization and shows how higher displacement speeds can be obtained using the synchronized vibrating system.

As depicted in Fig. 9, for *A* to *C* without force provided by the vibrating platform, the force developed by the three piezo-actuators of the robot could be sufficiently large (provided that the robot is made sensibly larger) to move the robot upward at an angle of 45°. It can be demonstrated that 45° is the optimal angle to move the robot at a greatest distance. Thus, using only its piezo-actuators, the robot can make a jump of distance *AC* and reach a height of *0B*. Instead of starting the jump at *A*, the robot can be synchronized with the vibrating platform to jump at D with the same angle of 45°. Precisely at *D*, the robot moves upward using a slight force while the vibrating surface moves downward. The robot will travel through instants *E*, *F*, *I*, prior to landing on the vibrating surface at instant *I* where the vibrating platform will carry the robot to *K* to begin another jumping cycle.

IV. Experimental Results

The experimental results presented here were gathered with the prototype shown in Figs. 3 and 8. The prototype measures about 12 mm × 12 mm × 10 mm. The legs of the robot consist of parallel-mode two-layer bimorphs of type PSI-5A4E from Piezo System Inc. with a length of 7.35 mm, a width of 0.5 mm, and a thickness of 0.5 mm. The vibration source is a DP-V011 shaker from Data Physics Corporation. The head expander was made of aluminum 6061T.

Fig. 11 shows the displacement velocities at various frequencies ranging from 2.0 kHz to 6.0 kHz (in [8], the resonant frequency of a bimorph of the same given dimensions was calculated to be 4.4 kHz) when the robot was actuated using 5.0 volts (the voltage presently used for the onboard electronics of the robot) and 3.3 volts (the voltage aimed to be used for the next version of the robot).

(a)

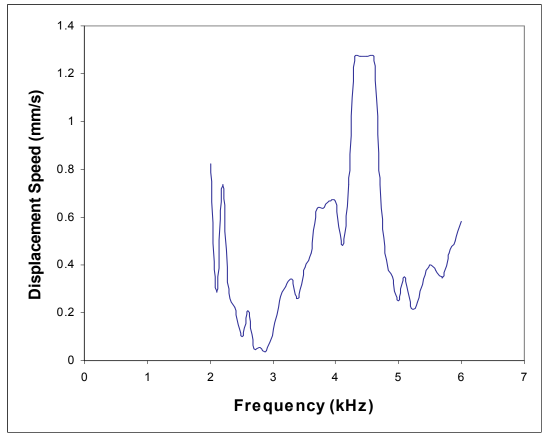

Fig. 11 (a) Displacement velocities of the robot versus the driving frequencies applied to its piezo-actuators when only the legs were activated at 3.3 volts.

(b)

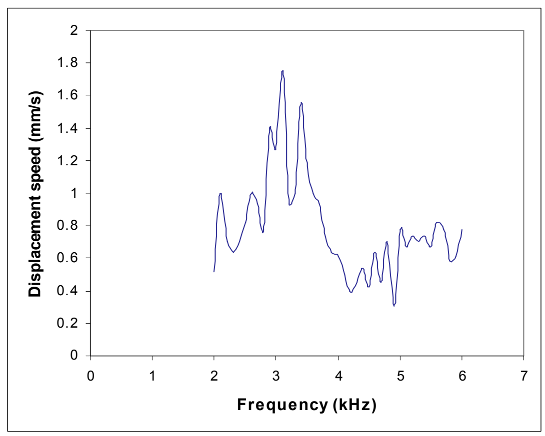

Fig. 11 (b) Displacement velocities of the robot versus the driving frequencies applied to its piezo-actuators when only the legs were activated at 5.0 volts.

(c)

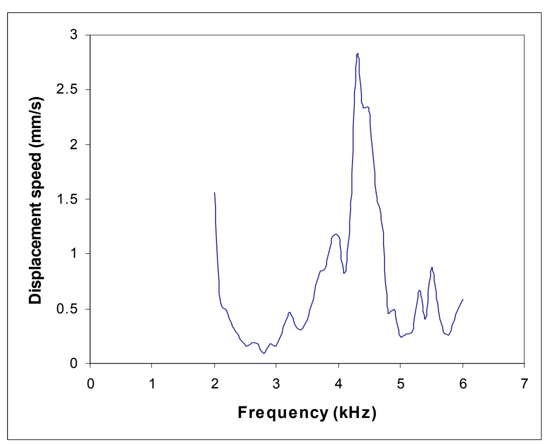

Fig. 11 (c) Displacement velocities of the robot versus the driving frequencies applied to its piezo-actuators when the vibrating surface was excited at 250 Hz and the legs were activated at 3.3 volts.

(d)

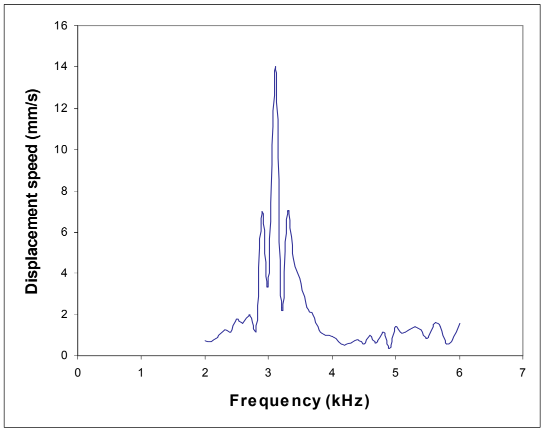

Fig. 11 (d) Displacement velocities of the robot versus the driving frequencies applied to its piezo-actuators when the vibrating surface was excited at 250 Hz and the legs were activated at 5.0 volts.

From the experimental data shown in Fig. 11, peak velocities are evaluated and summarized in Table 1. Although the piezo-actuators without the help of the vibrating platform were sufficient to move the robot, a significant increase (a factor of 9 in this particular set-up) of the displacement speed of the robot was recorded when the additional force provided by the vibrating platform was used.

Preliminary evaluation of the system performance demonstrated that the locomotion principle presented in this paper can provide very promising actuation mechanisms for the future NanoWalker robot. It showed that the application of such a locomotion principle can result in a higher displacement of the robot as expected. However, in order to reach micro- or nanometer positioning, further system development is required. The design parameters for such systems is expected to be a real challenge and is recommended to be obtained through the analysis of experimental data rather than through modeling.

TABLE 1
Peak velocities obtained from graphs presented in Figs. 11 (a)-(d).

Driving voltage of legs	Peak velocity when actuated with only legs	Peak velocity when actuated with legs and vibrating surface
3.3 volts	1.3 mm/s	2.7 mm/s
5.0 volts	1.7 mm/s	14 mm/s

V. Conclusion

A new locomotion based on synchronized vibrating actuation mechanisms for a fleet of miniature instrumented robots has been briefly presented. The locomotion method uses a combination of embedded piezo-actuators based on a three-legged architecture that can be supplemented by a software-controlled vibrating platform to achieve further miniaturization of the robots and higher displacement speeds. Although the proposed actuation system has great potentials for such high-performance platform, the conception of an adequate control strategy and automatism remains critical issues to apply this method.

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