Modeling and Experimental Study of a Two Modes Excitation Travelling Wave Piezoelectric Miniature Robot

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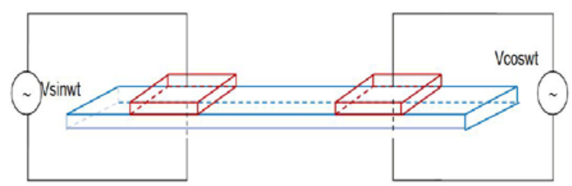
Abstract:
In this paper, the operation principle of a new type of piezoelectric miniature robot for terrestrial locomotion is presented. A prototype consists of an aluminum beam structure, with two non-collocated piezoelectric patches bonded on its surface was fabricated and tested to demonstrate the generation of a traveling wave based on a two modes excitation on the beam for propulsion. A numerical model was developed and used to study and optimize the generated motion of the robot. An experimental characterization of the robot has been done and results are given in this paper.
Keywords: Piezoelectric miniature robot, terrestrial locomotion, a two modes excitation, modeling, experimental characterization.

1. Introduction

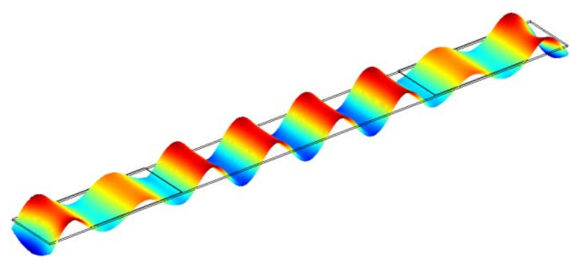
Piezoelectric miniature robots are mobiles robots with a size of few cm^3, a motion range of at least several times the robots body length and actuated by piezoelectric materials. An overview of locomotion principles for piezoelectric miniature robots can be found in [1, 2], where many designs and mechanisms are cited for piezoelectric miniature robots on a solid substrate. The idea is inspired from linear traveling wave ultrasonic motor [3, 4] and it is applied for robotics systems. It consists of the generation of a traveling wave in the beam structure permitting its movement on a solid substrate. A prototype has been manufactured to demonstrate the generation of the traveling wave on the beam. In this paper, we will present the operation principle of the robot, its structure modelling and design as well as its fabrication. At the end, a study of the effect of some parameters (applied voltage, embedded mass, mechanical load) on the performance of the system is presented experimentally.

2. Operation principle of the mini-robot

Our design consists of an aluminum beam structure, with two non-collocated piezoelectric patches bonded on its surface. The idea is to generate a traveling wave in the beam structure to move it on a solid substrate without using legs. Due to this aim, the two piezoelectric patches are used as actuators producing the mechanical displacement of the beam by applying simultaneously two neighbored natural mode shapes of the beam at the same frequency but with a phase difference of 90°, as shown Fig. 1.a. The vibration can be approximated as the superposition of these two modes; this is called a two modes excitation [3-5].



a) Operation principle



b) Traveling wave on the beam

Fig.1: *Studied device*

3. Modelling, design and fabrication

A Finite Element Method (FEM) is used to model the robot structure in order to determine optimal geometric parameters of the system (Fig.2), type of material used for the beam, optimal operating frequency and applied voltage needed.
Basing on Euler-Bernoulli assumptions for a beam structure, the linear constitutive relations and by applying Hamilton principles, we obtain the variational equation governing the mechanical and piezoelectric part of the system. Then a FEM is used to obtain the variational equation in matrix form, taking into account the damping behavior of the real system. Readers can refer to [6] for details about governing equations, variational principle and FEM applied to this system. Our goal is to demonstrate

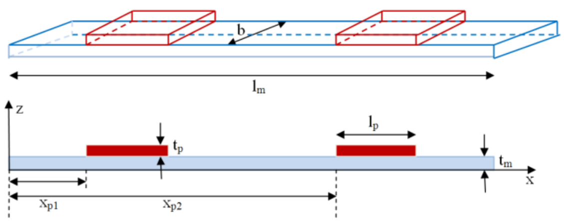


Fig. 2: *Geometric parameters for the system*

the generation of a traveling wave on the beam; a prototype has been manufactured due to this aim. Dimensions of the beam are (180 × 17 × 0.5 mm) and positions of the piezoelectric patches ($x_{p1} = 24\,mm$ & $x_{p2} = 126\,mm$) were fixed, we still have to know dimensions of the piezoelectric patches, and the type of elastic material used for the beam. Width of the piezoelectric patches was chosen to be the same as the beam width. Length of the piezoelectric patches was chosen to have the best compromise between displacement and traveling wave performance and it leads to 35 mm of length. Thickness for the piezoelectric patches and type of material used for the beam were chosen using the developed model to obtain a compromise between the maximum transverse displacement and the maximum frequency. Due to this aim, we have considered the case when one piezoelectric patch is used as actuator while the other is open circuited, then according to Fig. 3 and Fig. 4, an aluminum beam and 0.27 mm thickness of PZT piezoelectric patches were chosen. Properties and geometric parameters for the PZT and the aluminum beam are given in table I.

Table 1: *Properties and geometric parameters of the system*

	PZT	Aluminium
Young's modulus c_m (Pa)	-	69×10^9
Poison's ratio $\boldsymbol{\upsilon_m}$	-	0.33
Volume density $\boldsymbol{\rho_p}$& $\boldsymbol{\rho_m}$ (kg.m^{-3})	7900	2700
Relative permittivity $\boldsymbol{\varepsilon^{\sigma}_{33r}}$	1282	-
Piezoelectric constant d_{31} (m.V^{-1})	- 1.3×10 10	-
Elastic compliances $\boldsymbol{s^E_{11}}$ (Pa^{-1})	1.3×10^{-11}	-
Max p-p electric field E_{max} (V.mm^{-1})	300	-
Max compressive strength $\boldsymbol{\sigma_{max}}$(Pa)	600×10^6	-
Length × width × thickness (mm^3)	32×17× 0.27	180 × 17× 0.5

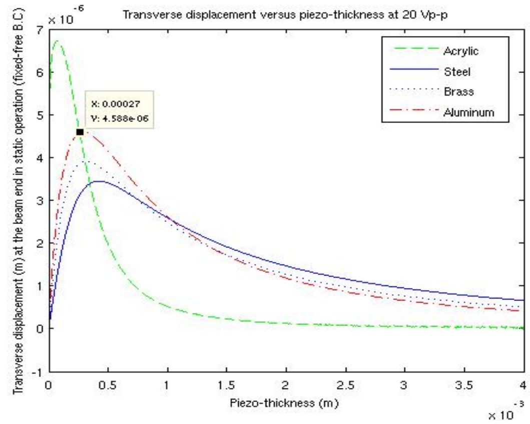


Fig. 3: *Displacement versus piezo-thickness for different beam material*

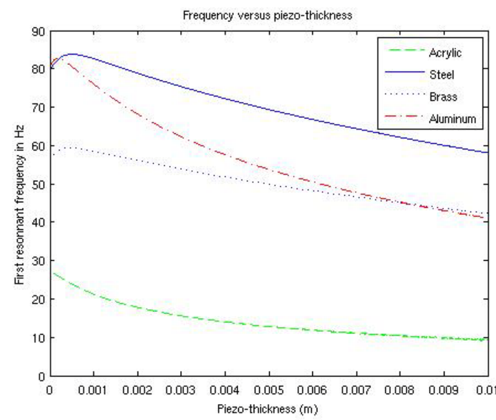


Fig. 4: *Frequency versus piezo-thickness for different beam material*

Our prototype is composed of three parts as shows Fig. 5. Two power amplifiers are used to amplify signal provided by the signal generator to the piezoelectric patches. It was found by simulation that there is no generation of travelling wave at low frequencies. At high frequencies the generated travelling wave changes direction according to the excitation frequency as shown in table 2. In this operation principle, two modes excitation must be applied simultaneously at the same frequency to generate travelling wave. It was shown by simulation also that a wave with a higher standing wave ratio is obtained at the resonance frequency.

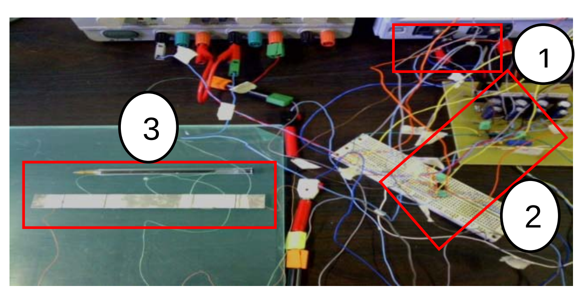


Fig. 5: *Prototype (1: Signal generator, 2: power amplifiers and 3: robot body)*

Table 2: *Wave propagation direction for different frequencies*

n	Frequency f_n	(kHz) f_{n+1}	f	Wave propagation direction
15	9	10.3	9.6	→
16	10.3	11.8	11	←
17	11.8	13	12.4	→
18	13	14.3	13.6	←

Fig 6 shows wave performance at the 17^{th} resonant frequency. It may be noted that travelling wave performance depends on piezoelectric patches positions. Also the resonant frequencies for the system depend on piezoelectric patches positions. At fixed piezoelectric patches positions, the optimal operating frequency for this piezoelectric miniature robot is that gives the better travelling wave performance. Figure 7 shows performance and directions of the travelling wave at 20 V amplitude. As we can see, Fig 7.d shows higher standing wave ratio, which means at this frequency the robot does not move. Fig. 7.b shows better travelling wave performance compared to others. In this case the system is excited at 11 kHz as indicated in table 2. This frequency is considered as the optimal operating frequency for the minirobot at these piezoelectric patches positions. Experimentally, the optimal operating frequency for this piezoelectric miniature robot is that gives the better robot speed and it was found equal to 11.3 kHz.

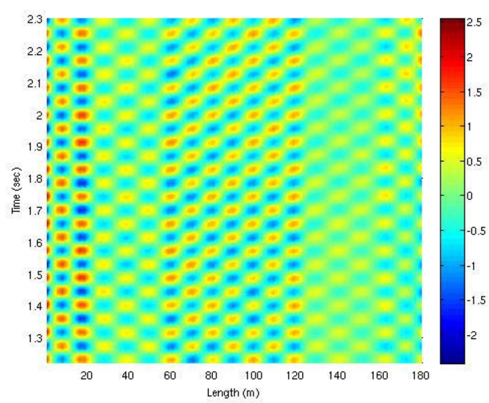
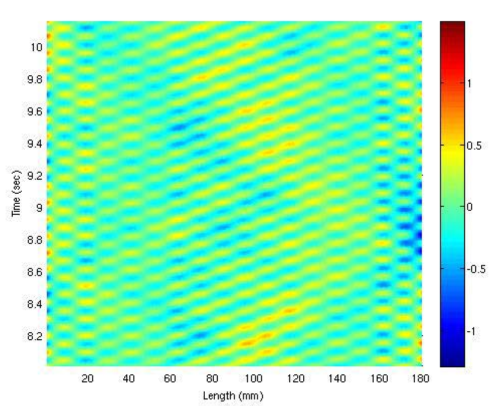
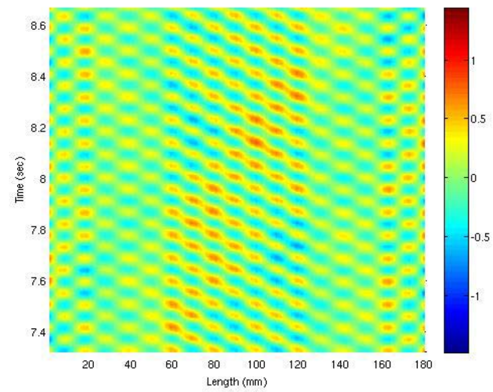


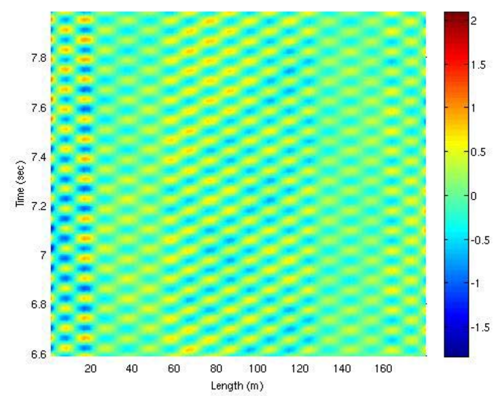
Fig. 6: *Wave at 11.8 kHz*



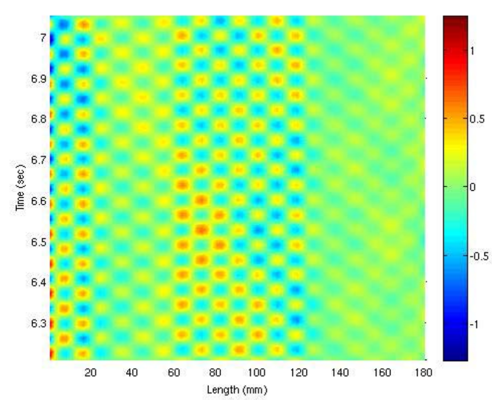
(a) Wave at 9.6 kHz



(b) Wave at 11 kHz



(c) Wave at 12.4 kHz



(d) Wave at 13.6 kHz

Fig. 7: *Transverse displacement in µm and traveling wave performance at 20 volt amplitude*

4. Robot characterization

Piezoelectric patches have 300 $V.mm^{-1}$ maximum peak to peak electric field (Table I), which means that the applied voltage must be less than 81V peak to peak at piezoelectric thickness equal to 0.27 mm. To characterize the robot, we measured the robot speed on a smooth glass flat surface for different applied voltage (Fig. 8) and the influence of embedded mass on the robot speed (Fig. 9).To determine the nominal operating point of the robot, we measured robot speed versus dragged load at a given applied voltage. Fig. 10 shows robot speed versus dragged mechanical load for different applied voltage, where it becomes easy to determine the maximum power point for the robot.

5. Conclusion

We designed and fabricated a prototype for a two modes excitation travelling wave piezoelectric miniature robot. This robot has an optimal operating frequency equal to 11.3 kHz, travelling at 131.5 mm/s at 30 V amplitude without embedded mass, has negligible consumption of power because the system is almost capacitive. At the same voltage, this robot can provide 432 μW (7.2 mN, 60 mm/s). It is convenient to study the influence of piezoelectric patches positions on the optimal operating frequency of the robot i.e. on the transverse displacement and traveling wave performance.

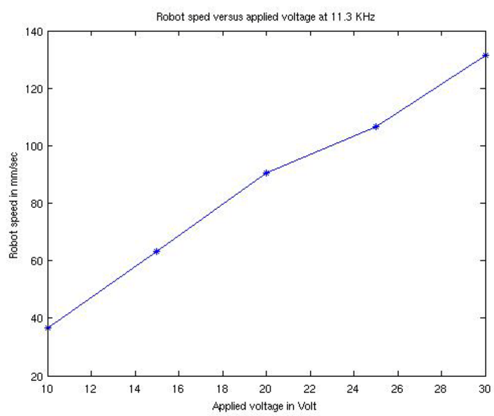


Fig. 8: *Robot speed versus applied voltage on a smooth glass flat surface*

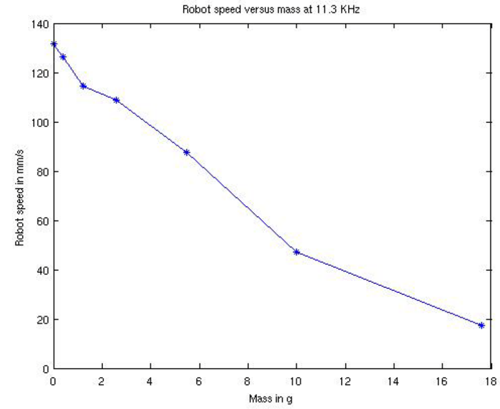


Fig. 9: *Robot speed versus embedded mass on a smooth glass flat surface*

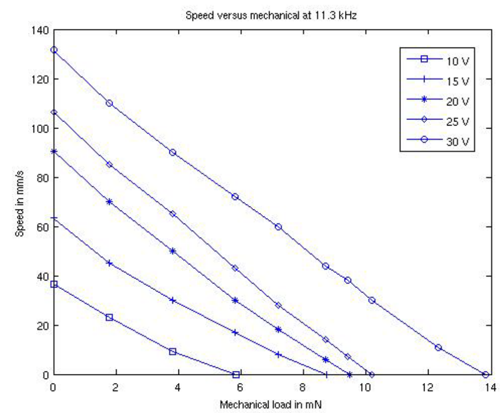


Fig. 10: *Speed versus mechanical load for different applied voltage at 11.3 kHz.*

References

[1] H. Hariri, Y. Bernard, A. Razek, "Locomotion principles for piezoelectric miniature robots ", " Proceedings of ACTUATOR 10", Bremen, DE, 14 June 2010, pp. 1015-1020.

[2] W. Driesen, ‘’Concept, modeing and experimental characterization of the modulated friction inertial drive (MFID), Locomotion principle: Application to mobile microrobots’’, Swiss federal institute of technology, Lausanne, PhD thesis.

[3] C. Hernandez, Y. Bernard, A. Razek, ‘’ Theoretical and experimental analysis of a two modes excitation linear motor using piezoelectric actuators’’, ‘’Proceeding of ACTUATOR10’’, 2010, p.21.

[4] G.H. Kim, J. W. Park, S. H. Jeong, ‘’ Analysis of dynamic characteristics for vibration of flexural beam in ultrasonic transport system’’, Journal of Mech. Sc. And Tech., 2009, vol. 23, pp. 1428-1434.

[5] B. Dehez, C. Vloebergh, F. Labrique, ‘’Study and optimization of traveling wave generation in finite-length beams’’, Journal of mathematics and computers in simulation, Vol. 81, Iss. 2, 2010, pp. 290-301.

[6] H. Hariri, Y. Bernard, A. Razek, ’’Finite element model of a beam structure with piezoelectric patches using RL shunt circuits’’, AC2011, 14th International Conference on active systems for dynamics markets, Darmstadt, Germany, 2011,pp.124-131.