



Sub-Gram In-Plane Vibration-Driven Robot with Inclined Legs [†]

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Abstract: This document reports the design, fabrication and performance of miniaturized locomotion systems employing flexible materials and 3D printed legs. The movement of the system was achieved by the first extensional mode of vibration of the platform of the robot and the inclination of the supporting legs. The structures were manufactured using a 30-mm-long piezoelectric polyvinylidene fluoride (PVDF) film as the robot platform, with manually added legs fabricated by stereolithography (SLA). Several speed measurements were performed for samples of 1- and 2-mm-long legs, at an angle of inclination of 45° and 60° to the PVDF film. The system was able to exceed a speed of 1 BL/s (body-lengths per second) to 25 V.

Keywords: extensional mode; miniaturized locomotion; piezoelectric; PVDF

1. Introduction

Despite the breakthroughs in the locomotion of robots on the macroscale, there is not a counterpart on the miniature scale. A recent review [1] pointed out the limitations of sub-gram systems. Locomotion based on legs is already well established for robotic platforms and might be a solution for miniaturization. Assuming a back-and-forth motion of the legs, a net displacement can be attained when the forward slip is not equal to the backward slip.

The motion of the legs can be induced by the generation of waves on the platform where the legs are attached. Waves might be either standing waves (SW) or travelling waves (TW). The combination of straight legs and SW was reported for the movement of sliders [1] or the locomotion of a platform [2]. Recent publications also demonstrated the use of TW and straight legs for conveyance applications [3], as well as robotic locomotion [4].

The use of inclined legs is also a common way of achieving an asymmetric slip. Numerous publications implemented this approach [5–7]. In most of these publications, a vertical displacement of the robot platform was required to induce the asymmetry and achieve a net horizontal motion.

Here, we also propose the use of inclined legs, but with a horizontal displacement of the platform. For that, an SW approach is selected: the generation of the first extensional mode of vibration of a free rectangular platform. The material of the platform is piezoelectric polyvinylidene fluoride (PVDF). This polymer allows for actuation, as well as for a low-cost, light-weight approach in the quest of miniaturization. Preliminary results demonstrated a locomotion speed of 42 mm/s for a 15.8 mg PVDF/legs combination.

2. Device Design

The core of our design relies on how to combine the extensional mode of vibration of the platform and the inclined legs.

The modal shape of this mode is calculated using Equation (1), where l is the maximum displacement, x is the position along the sample with $x = 0$ at one of the edges of the sample and L is the length of the sample. As can be seen in Figure 1, each side stretches in one direction, reaching its maximum at the edges. Therefore, the legs will be located as close to the edges as possible.

$$u = l \cos(\pi x/L) \quad (1)$$

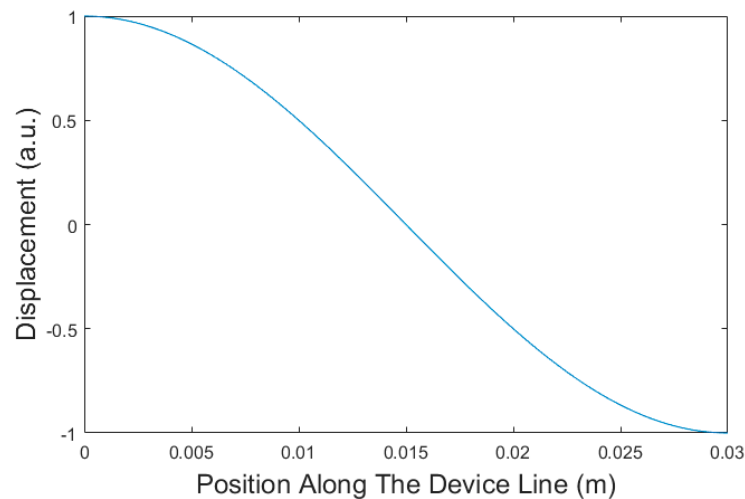


Figure 1. Displacement along the sample due to the extensional mode.

Figure 2 shows the PVDF platform together with the legs. Both the orientation and the location of the legs are important parameters to consider. With the orientation of the figure, the inclined legs show a higher friction when moving to the left than to the right [8]. Besides, due to their location, each leg moves in an opposing direction, which results in a net movement of the platform to the right.

The frequency of vibration of the extensional mode was obtained by Equation (2) for a free-free beam, as indicated by reference [9].

$$f_0 = \frac{1}{2L} \sqrt{\frac{E}{\rho}} \quad (2)$$

where ρ is the density of the material and E is Young's module of the beam.

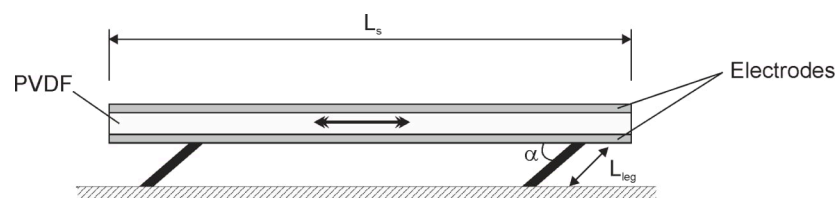


Figure 2. Schematic diagram of the device design. The device consists of a piezoelectric polyvinylidene fluoride (PVDF) piezoelectric film metalized at both sides. Two pairs of 3D-printed legs were manually attached to the bottom side of the PVDF film.

3. Materials and Methods

The platform of the robot was a 30- μ m-thick uniaxially oriented piezoelectric PVDF layer, metalized on both sides with Cu/Ni, commercially available from Goodfellow. A die cut machine (Silver Bullet) was used to define the size of the robot: 30 mm long and 5 mm wide. With these

dimensions, the theoretical frequency of the extensional mode was 17.7 kHz, according to Equation (2). Table 1 shows the PVDF properties used for the calculation.

Table 1. Properties used in the analysis.

| Parameter | Symbol | Value | Unit |
|----------------------------------|--------|-------|-----------------|
| PVDF density (kg/m^3) | ρ | 1760 | kg/m^3 |
| PVDF Young's modulus (GPa) | E | 2 | GPa |

Figure 3 shows a picture of the fabricated U-shaped legs. A stereolithography (SLA) 3D printer (B9 Core 530) was used for the fabrication. The material was nylon resin. The length and the angle of inclination of the legs were varied; 1-mm- and 2-mm-long legs were fabricated, at two different angles of inclination to the PVDF platform, 45° and 60° . The legs were attached to the platform by means of epoxy resin, an elastic adhesive that prevented stiffening the joint. For electrical access to the metallizations of the PVDF layer, 25- μm -thick aluminium wire was used, to minimize loading effects. The connection between the aluminium wire and the PVDF metallizations was made by electric paint (Bare Conductive), coated with a layer of silver paint to improve conductance. Figure 4 shows a picture of the whole system, PVDF plus legs and electrical connections.



Figure 3. Photograph of one of the U-shaped legs.

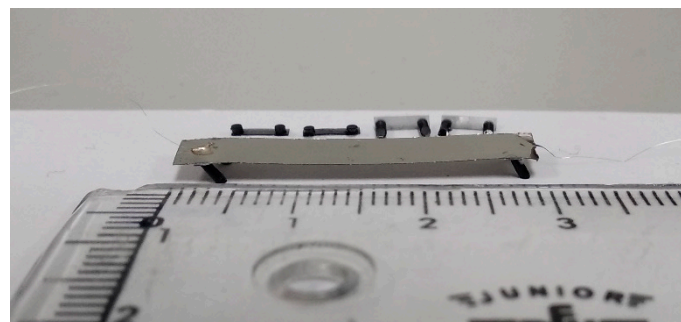


Figure 4. Photograph of the whole system.

The presence of the extensional mode was detected with the help of an impedance analyzer (4294A Agilent). Additionally, for the speed characterization of the robot, a set-up was mounted with two infrared LEDs, separated 10 cm and connected to a frequency counter to detect the pass of the robot.

4. Results

Figure 5 shows the electrical conductance of a sample with 2-mm-long legs at an angle of 45° . The maximum response corresponding to the extensional mode was located at about 15.5 kHz. This would be the frequency of actuation of the robot. For all the samples under study, the frequency of

the maximum conductance of the extensional mode was in the range between 15 and 17 kHz. The difference between the theoretical frequency and the measurements might be related to the mass added by the legs and manufacturing defects.

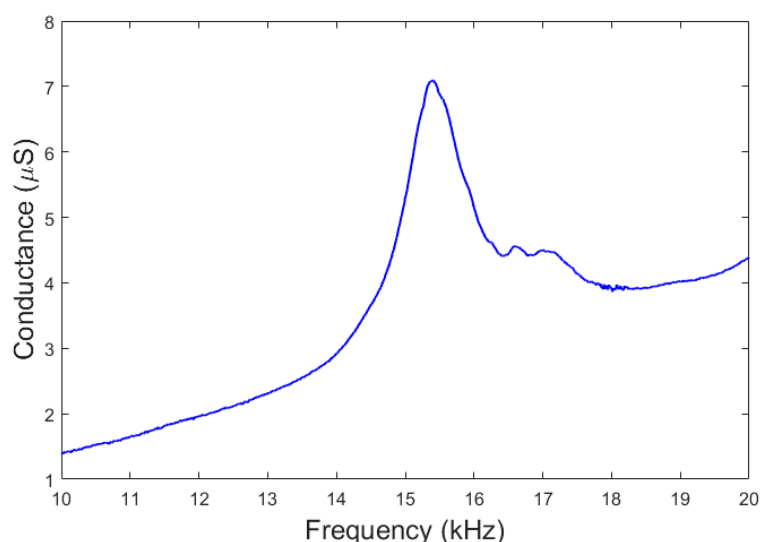


Figure 5. Measured conductance of a sample with a 2-mm-long leg at an angle of 45°.

Figure 6 shows the speed of the different samples versus applied voltage. No results were obtained for the robot with 1-mm-long legs at an angle of 45°, mainly due to contact problems between the legs and the floor. A speed as high as 40 mm/s was obtained for a voltage of 25 V.

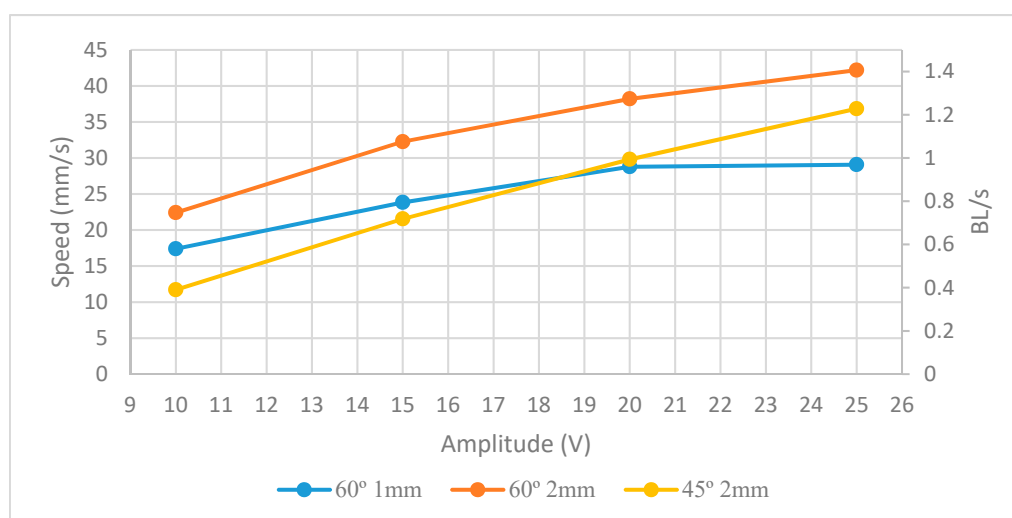


Figure 6. Results from the kinetic characterization of the samples.

5. Conclusions

This work demonstrates the achievement of locomotion by the combination of an extensional mode of vibration and inclined legs. The use of flexible materials resulted in a sub-gram system with a speed of about 1 BL/s (body-lengths per second) at a voltage of 25 V.

Author Contributions: J.H.-G. and J.L.S.-R. conceived and designed the experiments; D.R.-C. and V.R.-D. performed the experiments and analyzed the data; D.R.-C. and J.H.-G. wrote the paper. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

| | |
|------|-------------------------|
| PVDF | Polyvinylidene fluoride |
| SLA | Stereolithography |
| SW | Standing waves |
| TW | Travelling waves |

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