Abstract: The miniaturization of robots with locomotion abilities is a challenge of significant technological impact in many applications where large-scale robots have physical or cost restrictions. Access to hostile environments, improving microfabrication processes, or advanced instrumentation are examples of their potential use. Here, we propose a miniature 20 mm long sub-gram robot with piezoelectric actuation whose direction of motion can be controlled. A differential drive approach was implemented in an H-shaped 3D-printed motor platform featuring two plate resonators linked at their center, with built-in legs. The locomotion was driven by the generation of standing waves on each plate by means of piezoelectric patches excited with burst signals. The control of the motion trajectory of the robot, either translation or rotation, was attained by adjusting the parameters of the actuation signals such as the applied voltage, the number of applied cycles, or the driving frequency. The robot demonstrated locomotion in bidirectional straight paths as long as 65 mm at 2 mm/s speed with a voltage amplitude of only 10 V, and forward and backward precise steps as low as 1 µm. The spinning of the robot could be controlled with turns as low as 0.013 deg. and angular speeds as high as 3 deg./s under the same conditions. The proposed device was able to describe complex trajectories of more than 160 mm, while carrying 70 times its own weight.

Keywords: robot; standing wave; piezoelectric; leg; miniature; steering; 3D printing

1. Introduction

Miniaturization of mobile robots is a growing field of research that has attracted increased attention over many years, despite the remaining challenges to overcome. The first generation of micro-robots was on the rise in the late 1980s and the early 1990s, targeting cm-sized, self-propelling, and climbing machines. Many industries and academic researchers have invested in the study of the principle of motion of various insects, in what could be considered the original period of ‘bio-inspired’ engineering [1]. However, the development of micro-machines and micro-robots is still a current topic of great interest. A recent article by St. Pierre et al. [2] highlighted the difficulties associated with the decrease in size of the robots concerning speed, control, and autonomy. The achievement of such miniature-sized robots would imply lower cost and accessibility to areas forbidden to larger robots [3].

The fabrication of miniature sub-gram robots is a remarkable feat, where different fabrication technologies and actuation techniques have demonstrated encouraging results [4–7]. Alternatively, 3D printing is a promising approach that allows for the manufacture of 3D objects by successive layer-by-layer deposition with high resolution and flexibility in geometry and materials [8–11]. When dealing with miniature robots, the minimum feature size of the 3D printing technique is a major determinant of the accuracy of the design. Besides, the stiffness of the material to be printed is a critical parameter to consider that affects the performance of the device from a mechanical point of view. Among the different
3D printing techniques, laser-based printers offer enough resolution when pursuing milli-sized robots [10], and a photopolymer with a tensile modulus up to 10 GPa after curing is already commercially available [12].

Regarding the actuation mechanism of small size robots, a wavelike motion of the body of the robot, with attached passive legs, is a well established approach. The combination of waves of standing nature (i.e., a vibration mode) with legs was already proposed in the seminal paper by He et al. [13] for slider motion. Recent articles have reported the achievement of standing-wave (SW) locomotion of robots at the mm-sized scale [14,15].

A step further is to steer the robot. Recent reports have shown the turning of milli-sized robots by only tuning the frequency of actuation of the device [11,16]. More complex steering techniques rely on individual control of the legs [17,18] or a differential-drive approach by independent control of each side of the robot [19–21].

The long-term target of our work is the development of a low-cost sub-gram autonomous robot capable of running through complex paths with high accuracy and requiring low voltage signals. The robot should be able to carry power, processing, communication, and sensing devices, with a good balance between control and agility. Several engineering challenges needed to be overcome to reach this goal, beginning with the design and manufacture of a sub-gram low-cost locomotion platform. In this regard, here, we propose a miniature 20 mm long sub-gram robot with piezoelectric actuation whose direction of motion can be controlled. The fabrication of the robots was based on 3D printing and the locomotion of the printed robots was controlled by the generation of standing waves (SW) associated with resonant bending modes. Various printing materials were considered but stiffer materials resulted in a better performance in terms of quality factor and conductance of the generated SWs. Regarding the steering technique, a differential drive approach was implemented by means of two legged plates, joined together at the middle length (H-shaped). The generation of SWs at each of the plates, together with the proper location of the legs, allowed for the bidirectional locomotion. The actuation was achieved by piezoelectric patches and the control of the motion path was attained by controlling parameters such as the frequency of actuation, the applied voltage, or the number of applied cycles (duty cycle). In terms of performance, the proper control of the signals applied to the plates allowed us to achieve a straight path at 2 mm/s speed, and to perform forward and backward reproducible steps with a resolution as low as 1 µm. In addition, the spinning of the robot could be controlled with turns as low as 0.013 deg. and angular speeds of 3 deg./s. With these optimizations, the proposed design demonstrated the accomplishment of complex trajectories of more than 160 mm while carrying a payload 70 times its own weight.

2. Device Design

Figure 1 shows the type of structure under consideration. The body of the robot consisted of a pair of rectangular plates with a length of \( L_s = 20 \text{ mm} \), width of \( W_s = 3 \text{ mm} \), and thickness of \( t_s = 0.85 \text{ mm} \), bound together by a light nexus of the same material. This nexus consists of a rectangular section bridge, with lengths \( (L_{nx}) \) varying from 1 to 3 mm. The actuation of the robot was carried out by lead zirconate titanate (PZT) piezoelectric patches that started at one edge and covered a given length \( (L_p) \) on each plate to be determined by design.

The locomotion of the robot was based on the generation of standing waves (SW) in the two plate resonators, in combination with an appropriate location of legs [13]. This configuration was successfully applied to the bidirectional linear motion of millimeter-sized robots by means of two consecutive flexural modes [15,22]. The two plates of our design could be considered as independent SW motors and were designed as such.

Here, we considered the flexural modes with five and six nodal lines along the length of the plate and no nodal lines along the width of the plate. Using a two-index naming convention representing the number of nodal lines along the length and the width, we will refer to these as the \((50)\) and \((60)\) modes. Figure 2 shows a 1D representation of
the considered mode shapes. In order to optimally excite either of these modes, the piezoelectric patch should cover the area at which the curvature of the mode shapes has a constant sign [15,22]. In our case, in the search of the ease of fabrication, a patch length of 5 mm on both plates allowed for an efficient actuation of both modes.

![PZT patches](image)

**Figure 1.** Schematic description of the twin-plate robot design.

The location of the legs is the key point of the SW-based bidirectional locomotion. Figure 2 shows where to locate them according to the criteria explained by He et al. [13]. We searched for positions that allowed for opposite movements for each modal vibration. Therefore, the location of the legs should be at the right of a crest (red areas) for a given modal shape, and to the left of the crest (blue areas) for a subsequent modal shape. Consequently, by tuning the frequency of actuation to the resonance frequency of these modes, the direction of the movement could be changed. The legs should be located where the blue and the red areas overlap, highlighted by the dashed rectangles in Figure 2, which results in five possible positions for locating the legs.

In search of a compromise between stability and friction losses, we decided to use a total of three legs attached to the robot: two legs at plate A, located at positions 1 and 4, and only one leg at position 3 for plate B. The size of the legs was optimized in a previous work for a similar SW-based motor [15]. A leg length of 1.1 mm and a diameter of 0.6 mm was chosen, so that the leg first resonance was much higher than the driving frequencies of the robot to prevent plate–leg coupling effects.

Our design allows for four different types of motion that can be seen in Figure 3. Each plate could be actuated on the (50) or (60) mode by applying sinusoidal signals at the corresponding resonant frequencies. By combining either of the modes on each of the two plates, four distinct movements could be obtained by differential drive: forward and backward translational movement and clockwise (CW) or counterclockwise (CCW) rotation of the robot.

Due to the asymmetries present on the structure caused by the leg distribution or the fabrication tolerances, the thrust exerted by the plates was not the same, despite applying the same signal to each one. This resulted in deviations from the ideal expected movement. To correct the trajectory, a fine-tuning of the signal applied to each of the plates was required to balance out the unwanted deviations. Both the voltage amplitude and the number of cycles of the actuation signal were chosen as the parameters for the adjustment, while the frequency of actuation was fixed to the value corresponding to the resonance frequency of the required modal shape. Burst-type signals were used, consisting of a finite number of sinusoidal cycles. The period of the burst signal, \( T_b = T_{ON} + T_{OFF} \) was fixed to one second. The duration \( T_{ON} \) of the active part of the signal was equivalent to the number of cycles times the period of the excitation signals (i.e., \( T_{ON} = \frac{\text{cycles}}{f_{drive}} \)). This gives a duty cycle \( D = \frac{T_{ON}}{T_b} = \frac{\text{cycles}}{f_{drive}} \times 100 \). These parameters are exemplified in Figure 4a.
Two alternative actuations and therefore balancing procedures were considered: either by voltage amplitude or by number of cycles. In the first one, depicted in Figure 4a, the same number of excitation cycles was applied on both plates and the thrust balance was achieved by adjusting the ratio of applied voltage amplitudes. In the second alternative, depicted in Figure 4b, the thrust was balanced by adjusting the number of cycles in the active part of the burst signals with the same voltage amplitude for both signals.

**Figure 2.** Schematics showing the location of the legs for standing wave (SW)-based locomotion with the (50) and (60) modes. Each colored half lobe represents the region where a leg produces a rightward or leftward movement of the robot. For bidirectional motion, legs should be located on the dashed vertical rectangles. Positions 1 and 4 were chosen for plate A and position 3 for plate B.

**Figure 3.** Graphical description of the four different types of motion of the robot. Each plate could be actuated either on the (50) or (60) mode for a bidirectional thrust.
Figure 4. Excitation voltage signals applied to the plate resonators A (red color) and B (blue color). Each burst signal is characterized by the voltage amplitude, the burst period \(T_b\), and the active period \(T_{ON}\). Two alternative actuations were considered: (a) both plates with the same number of sinusoidal cycles per burst but different voltages, or (b) both plates with the same voltage amplitude but different number of cycles.

3. Materials and Methods

Following the design guidelines in the previous section, several robots were fabricated, as shown in Figure 5. The procedure is as follows.

![Figure 5. Photograph of one of the fabricated robots. The two legs of plate A can be observed. Electrical access to the PZT patches was made through 25 μm silver insulated wires.](image)

First, an H-shape supporting platform consisting of two 20 mm long, 0.85 mm thick and 3 mm wide plates attached by a nexus was fabricated on a highly glass-filled resin (Formlabs Rigid 10 K resin [23]) in a Form 3 stereolithography (SLA) printer by Formlabs. Different sizes of the central nexus were considered with lengths varying from 1 to 3 mm and cross sections of \(0.2 \times 0.2\) mm\(^2\) and \(0.6 \times 0.85\) mm\(^2\).

The monolithic structure included 1.1 mm long cylindrical legs with a 0.6 mm diameter. Two legs were printed at the center of the width of plate A and an additional leg at the center of the width of plate B, at those positions along the length described in the design section. After printing, the structure was cured with ultraviolet (UV) light and heat treatment for 60 min at 70 °C, acquiring its final properties (Table 1).

| Table 1. Material properties of the different components used in the robot fabrication. |
|----------------|----------------|----------------|----------------|
| **Element**    | **Thickness (mm)** | **Young’s Modulus (GPa)** | **Density (kg/m\(^3\))** |
| PZT patches    | \(t_p = 0.1\)     | 62              | 6700            |
| Rigid 10K resin| \(t_s = 0.85\)     | 10              | 1670            |

Next, two electroded PZT patches (PIC 255 from PI Ceramic GmbH, Lederhose, Germany) with a thickness \(t_p = 100\) μm and a width of 3.5 mm, slightly wider than the
plate to allow electrical access to the bottom electrode, were glued to each printed plate by means of a cyanoacrylate adhesive (Loctite, Düsseldorf, Germany). The length of the patch was 5 mm, according to Figure 2. Additionally, 25 µm in diameter silver insulated wires were attached to the piezoelectric patches for electrical connection to the external signal generator. The mechanical properties of the PZT patches can be found in Table 1.

The kinetic characterization was carried out employing two different recording cameras. One with high speed, high resolution, and a large field of view (Logitech Streamcam) was used to track the robot while performing large displacements. This camera covered a 23 × 13 cm² area, with a spatial resolution of 120 microns at 60 frames per second (fps). In addition, a microscope camera consisting of a CMOS sensor (Throcam DCC1545M) coupled to an optic tube was used to record the position and the orientation of the robot while performing small steps. This camera covered a 2 × 2 mm², with a spatial resolution of 100 nm at 30 fps. The cameras were computer controlled as was the signal generator (Tektronix AFG 3000 series) used to apply the required sinusoidal signals to generate the SW in the plates. The robot demonstrated locomotion in a wide variety of surfaces such as glass, polyimide, polyethylene naphthalate (PEN), cast aluminum, or a flat surface made of the same material of the robot platform, Rigid 10K resin. However, the glass surface showed better results in terms of performance and trajectory control, so the experiments were all carried out with the robot lying on a leveled glass surface. Finally, the recorded videos were processed by a motion tracking algorithm programmed in MATLAB.

4. Results

Prior to the subsequent kinetic analysis, the electrical response of the resonators was characterized by means of an impedance spectrum analysis. A 4294A Agilent impedance analyzer was used to record the conductance versus frequency of the different modes of vibration on each of the two plate resonators that comprised the robots. The figures of merit of the electrical response such as the quality factor, the resonant frequency, and the peak conductance were calculated through the fitting of these impedance measurements to a modified Butterworth–Van-Dyke equivalent electrical model circuit [24]. Besides, the detected impedance peaks were associated with the corresponding flexural modes with the help of a scanning laser Doppler vibrometer (Polytec MSV 400).

Figure 6 shows the conductance spectra of one of the fabricated robots. The H-shaped platform, comprising the two plates with legs and the joint linking the plates, was printed as a monolithic part, so the obtained resonant frequencies were determined by the whole structure. As can be seen, there were two clear peaks that were identified as the (50) and (60) modes. The figures of merit of these impedance peaks are shown in Table 2. The resonant frequency of the (50) and (60) modes were 59 and 86 kHz, respectively, while similar Q-factors around 26 and motional conductance in between 65 and 117 µS were estimated. Similar results were obtained for all the fabricated samples with the same nominal dimensions of the plates. Differences in the resonant frequencies below 2% were obtained among the fabricated samples, demonstrating the reproducibility of the process.

| Resonant Mode | (50) Mode | (60) Mode |
|---------------|-----------|-----------|
| Plate Frequency | Q-Factor | ∆G (µS) | Frequency | Q-Factor | ∆G (µS) |
| A | 59.3 | 28 | 65 | 85.8 | 24 | 79 |
| B | 59.2 | 27 | 72 | 86.1 | 25 | 117 |

Once the electrical response of the constituent plates was analyzed, the kinetic characterization of the robot was addressed. First of all, the determination of the appropriate excitation signals for a thrust balance in all four basic movements in Figure 3 was accomplished. Figure 7 shows the results corresponding to the fine tuning of amplitudes to balance out the deviations from the forward motion. As can be seen in Figure 7a, the
different ratios of the applied voltage from plates A to B resulted in a range of trajectories with dominant forward motion. Figure 7b depicts the off-axis absolute deviation (Y-displacement to X-displacement ratio) of these trajectories. The ratio of voltages with the lowest deviation from the X-axis was then chosen for this value of equal excitation cycles. The same procedure was performed for the backward movement and for the two turning possibilities in Figure 3, minimizing the displacement of the robot’s center of rotation, obtaining the voltage ratios for a balanced thrust in every case. Similarly, this procedure could be performed for equal amplitude of applied voltages on both plates, but different ratios of number of excitation cycles.

Figure 6. Conductance spectra of plates A and B of one of the fabricated robots. The main peaks were identified as the (50) and (60) modes.

Figure 7. (a) Forward motion trajectories for different ratios of applied voltages on each plate. (b) Percentual absolute deviation off the X-axis displacement in forward motion for different ratios of applied voltages on each plate. All experiments were carried out at a constant number of excitation cycles of 7000 on both plates.

4.1. Speed Control

Figure 8 shows the results from the speed characterization for the forward and backward locomotion in Figure 3. The thrust of the plates was balanced following the above-
described procedures, allowing the robot to make linear displacements up to 65 mm with a controlled deviation off the X-axis. The large FOV camera setup was used in these experiments.

Figure 8a,b shows the mean speed of the robot for forward motion, where both plates were excited at the (50) mode resonant frequency. The results from the balancing procedure are also depicted in Figure 8a,b, with markers representing the combinations for a balanced motion by voltage amplitude or excitation cycles, respectively. As can be seen, both procedures allowed reaching a maximum speed of about 1.85 mm/s by (i) applying 6 V and 16,000 cycles on plate A and 6 V and 6000 cycles to plate B or (ii) applying 6 V and 16,000 cycles to plate A and 3 V and 16,000 cycles to plate B. Similar results were obtained for other input combinations. Therefore, for a balanced forward motion, plate A required twice as much power than plate B, either by applying a 2:1 voltage ratio at equal number of cycles or a 8:3 number of cycles ratio at equal applied voltage.

The backward motion (Figure 8c,d), where both resonators were excited at (60) mode resonant frequency, showed analogous results. The mean speed was lower when compared to the forward motion, and higher voltage amplitudes were required. Similar differences were found in bidirectional SW robots implemented in glass in [15] and might be attributed to the tight margin for the location of the legs to achieve bidirectional movement for the SW-based approach. Finally, in this case, the balancing ratios by voltage amplitude and excitation cycles were 0.6 and 0.5, respectively.

![Figure 8](image-url)

Figure 8. Results of translational speeds (solid lines and left vertical axes) in the forward and backward motions of Figure 3. Each color represents a different voltage amplitude, $V_A = V_B$, (a,c) or a different number of excitation cycles, $C_A = C_B$, (b,d) applied on both plates. The particular combinations of the number of cycles or the voltage amplitudes required for a balanced motion are represented with markers related to the right vertical axes.

The implemented differential drive allowed for CCW and CW rotations. Figure 9 shows the results from the angular speed characterization for the two turning possibilities in Figure 3. The thrust of the motors was balanced as in the previous experiments, allowing the robot to make rotations up to 360 deg., recorded with the large FOV camera setup. An
angular speed of above 3 deg./s was obtained for both directions using either the same voltage (Figure 9a,c) or the same number of excitation cycles (Figure 9b,d) on both plates.

In addition, as can be inferred from the balancing results in Figure 9, regardless of the sense of rotation, the plate actuated with the (50) mode, (plate A in CCW and plate B in CW) required about three times a lower number of cycles or applied voltage. This could also be attributed to the non-ideal leg location for bidirectional SW robots [15].

![Figure 9](image-url) Results of angular speeds (solid lines and left vertical axes) in the CCW and CW motions of Figure 3. Each color represents a different voltage amplitude, \( V_A = V_B \), (a,c) or a different number of excitation cycles, \( C_A = C_B \), (b,d) applied on both plates. The particular combinations of the number of cycles or the voltage amplitudes required for a balanced motion are represented with markers related to the right vertical axes.

4.2. Positional Control

One of the main advantages of the actuation strategy consisting of burst signals is the capability of the robot to move in discrete steps with high resolution. We studied the positional capabilities of the robot by reducing the supplied energy of the excitation signals in search of the smallest reproducible translation or rotation. Figure 10 shows the results from the experiments where a reduced number of cycles was equally applied to both plates. In this case, the balancing was performed by applying different voltage ratios to each plate while recording the robot movement with the high-resolution recording camera setup.

Regarding translational movements, as can be seen in Figure 10a,c, the step length could be decreased to less than \( 1 \mu m \). This value was close to the limit of detection of the used setup, so lower translational steps could be achievable. The forward motion balance was also reached for a \( 2:1 \) voltage ratio, as in the speed experiments (see Figure 8b), and a decreasing trend of the step size with the number of cycles or the application voltage was also observed. In contrast, the backward motion balance was reached at a \( 3:4 \) voltage ratio and required higher voltages to get to the minimum detectable step, than in forward
motion. The decreasing trend with the number of excitation cycles was not so prominent when considering the applied voltage.

Figure 10b,d shows the results of the CCW and CW movements, respectively, when the number of excitation cycles were reduced to less than 2000. The minimum turn was 0.02 deg., but voltages above 6 V were required to produce detectable rotations. The balance was reached at a 2:1 voltage ratio in the CW rotations, and similar but not so consistent results were obtained for the CCW turns.

A summary of the main results from the speed and positional characteristics of the robot is shown in Table 3. The maximum speeds were taken from the results with a $T_s = 1$ s and the upper limits of the experimental ranges (10 V and 16,000 cycles) while the minimum steps were taken from the experiments with the lower input limits of each type of motion.

![Graphs showing results of minimum translational steps and turns.](image)

**Figure 10.** Results in terms of minimum translational steps and turns (solid lines related to the left vertical axes) from the positional experiments in the four different types of movement of Figure 3. Each color represents a different number of excitation cycles applied on both plates ($C_A = C_B$). For a balanced motion, different combinations of applied voltages, noted with markers and related to the right vertical axes, were required.

**Table 3.** Summary of the main results from the kinetic characterization of the robots.

| Type of Motion    | Maximum Speed | Minimum Movement |
|-------------------|---------------|------------------|
| Forward           | 1.85 mm/s     | 1 µm             |
| Backward          | 0.6 mm/s      | 0.4 µm           |
| Counterclockwise  | 3 deg./s      | 0.016 deg.       |
| Clockwise         | 4.7 deg./s    | 0.013 deg.       |

4.3. Mass Loading

The effect of mass loading on the performance of the robots was also investigated. Figure 11 shows the robot speeds for the four movements depicted in Figure 3 for different
payloads and two distinct applied voltages of 5 V and 10 V using the large FOV camera setup. The excitation cycles were used to balance the motion, with values around 7000 for the dominant plate on each basic movement (right in the middle of the range used in the experiments of Figures 8 and 9). As can be seen, the robot was able to carry 15 g, 70 times its own weight, at 0.8 mm/s and 0.2 mm/s for forward and backward motion, respectively. Additionally, the robot was able to develop angular speeds of 2.5 deg./s and 1.1 deg./s for the CCW and CW directions, respectively, at the maximum applied voltage. The loading capacities of our proposed design make it suitable for autonomous applications, where the robot should carry onboard circuits including the control and the power systems, with a total weight below our achieved payload [25,26].

![Figure 11](image_url)

**Figure 11.** Translational and rotational speeds for different payloads and two applied voltages.

It is also noticeable from the results in Figure 11 that a maximum in the robot speed was found for loading masses in the range of 1 to 3 g. This maximum could be attributed to a compromise between the frictional forces, which increase with the addition of mass, and the vibration amplitude, which decreases due to the added mass damping.

In addition, Table 4 shows the blocking force of the robot under different mass loadings. The force was measured while the robot contacted a force sensor (Honeywell FSG Series) with the actuation voltage applied. A maximum blocking force of 10 mN was measured for a payload of 15 g and a continuous excitation of 10 V, while the robot was moving forward. Similar blocking force values were obtained in glass-based single-plate robots with SW actuation but for half the mass loading [15].

**Table 4.** Blocking force of the robot actuated on forward-direction movement for various payload and voltage conditions.

| Voltage (V) | 0   | 1   | 3   | 7.5 | 15  | 25  |
|------------|-----|-----|-----|-----|-----|-----|
| 5          | 0.3 ± 0.1 | 1.1 ± 0.1 | 2.0 ± 0.2 | 3.5 ± 0.1 | 3.7 ± 0.1 | 2.8 ± 0.1 |
| 7.5        | 0.3 ± 0.1 | 1.5 ± 0.1 | 2.4 ± 0.1 | 5.3 ± 0.1 | 7.0 ± 0.3 | 5.3 ± 0.4 |
| 10         | 0.6 ± 0.1 | 1.9 ± 0.1 | 2.8 ± 0.1 | 7.0 ± 0.3 | 10 ± 0.3 | 9.4 ± 0.5 |

4.4. Complex Trajectory

Finally, the kinetic performance, the trajectory control, and the mass loading capabilities of the proposed design were tested through a series of preprogrammed sequences of movements. No real-time control strategy was used in these experiments. The robot was loaded with 15 g and actuated in such a way that a right triangular trajectory and a square path were described at maximum speed for 10 V and $T_b = 0.5$ s. The same adjustment ratios as in the previous experiments with $T_b = 1$ s were used, demonstrating the validity of the control procedure for a different burst signal period. Figure 12 shows the results of
the performance of these paths, and the video experiments, recorded in the larger FOV setup, are provided in Supplementary Videos S1 and S2.

![Figure 12](image_url)

Figure 12. Results from the complex trajectory experiments, describing a 50 mm side right triangle (figures on the left) and a 40 mm side square (figures on the right). Top figures (a,c) show the robot position and orientation at some time instants of the preprogramed trajectory (red line). Bottom figures (b,d) detail the X- and Y-position and orientation of each trajectory vs. time and the sequence of resonant frequencies on plate A \((f_A)\) and plate B \((f_B)\) for actuation at the \((50)\) or \((60)\) modes.

As it can be seen in Figure 12a, the robot was able to describe a closed, right triangular trajectory of a 5 cm side in less than 200 s. The sequence of movements can be drawn from Figure 12b, where the position and orientation of the robot vs. time are depicted. The most challenging steps were a 330 deg. CCW turn (with less than 20 mm deviation in the X and Y axis) and a 65 mm long backward travel (with only 17 deg. orientation deviation). These deviations can be attributed to the mechanical stress of the wires.

Similar results were obtained with the square trajectory in Figure 12c. There, the robot performed both 90 deg. CW and CCW turns as well as 40 mm long forward and backward travels. As can be seen in Figure 12d, comparable deviations were measured in this trajectory, which demonstrated a promising trajectory control.
4.5. Performance Comparison

Table 5 summarizes a performance comparison of recent publications about miniaturized locomotion systems including our present robot. As can be seen, our proposed design is the only sub-gram robot with 2 degrees of freedom and a bidirectional motion among these references, featuring a minimum turning radius below 10 microns and a positional and rotational precision as low as 400 nm and 0.013 deg., respectively. In addition, the low-cost 3D printing fabrication technology used in our robot allows for an affordable platform in contrast to the more expensive MEMS or nanolithography printing technologies.

Table 5. Performance comparison of the most recent publications of miniaturized locomotion systems including our present robot. Unavailable data are indicated as “n.a.”.

| Reference | Size (mm³) | Mass (mg) | Fabrication Technology | Actuation | DOF | Bidirectional | Autonomous | Tethered | Voltage (V) | Power (mW) | Payload (g) | Speed (BL/s) | Resolution (nm) |
|-----------|------------|-----------|------------------------|-----------|-----|---------------|------------|----------|-------------|------------|-------------|--------------|----------------|
| [5]       | 2.5 × 1.6 × 0.7 | 1        | Nano-3DP               | Magnetic  | 1   | No            | No         | 2        | 897         | 0          | 14.9        | n.a.         |                |
| [4]       | 8.5 × 4 × 0.5 | 10       | MEMS                   | Electrostatic | 1   | No            | Yes        | 50       | 0.01        | 0          | 7 × 10⁻⁴     | n.a.         |                |
| [7]       | 5 × 5 × 0.5  | 18       | MEMS                   | Electrostatic | 1   | No            | No         | 80       | 0.01        | 0          | 9.2         | n.a.         |                |
| [6]       | 4 × 4 × 5    | 25       | MEMS                   | Magnetic   | 1   | No            | No         | n.a.     | 0.51        | 0          | 4.4         | n.a.         |                |
| [3]       | 30 × 15 × 0.1 | 64       | Laminates              | Piezoelectric | 1   | No            | No         | Yes      | 200         | 0.34       | 4           | 2.10⁶        |                |
| [1]       | 30 × 15 × 0.1 | 65       | Laminates              | Piezoelectric | 2   | No            | No         | Yes      | 250         | 0.18       | 7.5         | n.a.         |                |
| [13]      | 15 × 5 × 0.5 | 80       | MEMS                   | Thermal    | 1   | No            | No         | Yes      | 18          | 1100       | 2.5         | 0.4          | n.a.         |
| Present work | 20 × 6 × 0.85 | 200 | 3DP                    | Piezoelectric | 2   | Yes           | No         | Yes      | 10          | 10         | 25          | 4.1          | 400           |
| [13]      | 12 × 8 × 6   | 200     | 3DP                    | Piezoelectric | 2   | No            | No         | Yes      | 40          | n.a.       | 13         | 5.2          | n.a.         |
| [3]       | 24 × 22 × 0.18 | 240 | Laminates              | Piezoelectric | 2   | Yes           | No         | No       | 250         | 397        | 1.66        | 1.13         | n.a.         |
| [31]      | 20 × 5 × 1   | 250     | Glass + 3DP            | Piezoelectric | 1   | Yes           | No         | Yes      | 30          | n.a.       | 7.5         | 12.5         | n.a.         |
| [28]      | 50 × 50 × 20 | 1270    | Laminates              | Piezoelectric | 2   | Yes           | Yes        | No       | 210         | 50         | 1.35        | 1000         |                |
| [13]      | 50 × 50 × 20 | 2400    | Laminates              | Piezoelectric | 2   | Yes           | Yes        | No       | 10          | 1660       | 0.44        | 0.6          | n.a.         |
| [28]      | 58 × 44 × 12 | 4.5 × 10⁴ | Machining              | Piezoelectric | 2   | Yes           | No         | Yes      | 230         | 6666       | 200         | 8.9          | 440          |
| [29]      | 200 × 200 × 40 | 5.6 × 10⁶ | Machining              | Piezoelectric | 2   | Yes           | No         | Yes      | 200         | n.a.       | 2.5         | 10³         | 0.003         | 16           |

Our robot demonstrated the potential to become a fully autonomous motion system, thanks to a large carrying capacity in combination with a lower estimated power consumption. It is worth pointing out that two untethered and autonomous sub-gram robots have already been reported: the work by Hollar et al. [4] based on the MEMS technology featuring lower speeds and higher voltages, and the work by Liang et al. [3], which required excitation voltages as high as 250 V. Finally, our proposed design demonstrated submicronometric positional resolutions competing only with the heavier steel-based systems.

5. Conclusions

This work reports the design, fabrication, and characterization of a miniature 20 mm long sub-gram robot whose direction of motion can be controlled. A differential drive approach was implemented in a H-shaped 3D-printed motor platform by means of two-legged plate resonators, joined together at the middle length. The generation of the SWs on each plate was achieved by piezoelectric patches and the control of the motion path was attained by adjusting the parameters of the burst excitation signals such as the applied voltage, the number of applied cycles, or the driving frequency.

In terms of performance, bidirectional straight paths as long as 65 mm at 2 mm/s speed with only 10 V excitation were achieved, and furthermore, forward and backward precise steps as low as 1 µm. The turning of the robot could be controlled with turns as low as 0.013 deg. and an angular speed as high as 3 deg./s under the same conditions. With these optimizations, the proposed device demonstrated the execution of complex trajectories of more than 160 mm while carrying 70 times its own weight.

Regarding the lifetime of the system, mechanical fatigue fracture was not observed in our 3D printed platforms, likely due to the high stiffness of the glass-filled resin material. In addition, there are no moving parts in the design that can be exposed to a considerable wear except the leg tip. Although the robots were working for more than 100 h during the experiments without a noticeable impact on the leg tip, more tests should be conducted including different surfaces to determine the actual lifetime of the system.
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