NOVA

University of Newcastle Research Online

nova.newcastle.edu.au

Rios, Shannon A.; Fleming, Andrew J.; Yong, Yuen Kuan "Design and characterization of a miniature monolithic piezoelectric hexapod robot". Originally published in Proceedings of the 2016 IEEE International Conference on Advanced Intelligent Mechatronics (AIM 2016) (Banff, Alberta, Canada 12-15 July, 2016) p. 982-986

Available from:

<http://dx.doi.org/10.1109/AIM.2016.7576897>

© 2016 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

Accessed from: <http://hdl.handle.net/1959.13/1321851>

Design and Characterization of a Miniature Monolithic Piezoelectric Hexapod Robot

Shannon A. Rios¹, Andrew J. Fleming² and Yuen Kuan Yong³

Abstract—This paper describes the design, construction and performance of a miniature monolithic piezoelectric hexapod robot. Locomotion is achieved by driving the piezoelectric elements at the mid point between the first and second resonance modes to produce an ambulatory motion. The monolithic robot was milled out of a single piece of outwardly poled piezoelectric bimorph using an ultrasonic milling machine. Silver electrodes were evaporated onto the bimorph to isolate the individual piezoelectric elements from each other. The leg end-effectors of the robot were milled from aluminum and a previously described lumped mass model was used to design the end-effectors such that the swinging and lifting resonance modes were closely matched. The finished robot attained an average swinging and lifting resonance frequency of 308 Hz and 323 Hz with a 1 Hz and 3 Hz spread between the legs respectively.

I. INTRODUCTION

There are many advantages to the miniaturization of autonomous robots. The reduction in size allows the robot access to restricted locations such as water pipes [1], through rubble [2], [3] and even inside the human body [4]. Another advantage is the potential reduction in cost and the possibility for disposable robots. It is also possible to power a miniature robot completely or partially from ambient energy sources such as light, electric fields, magnetic fields or vibration [5].

A significant challenge when designing a miniature robot is to devise a construction method that produces repeatable performance. An ideal construction method would automate as much of the assembly process as possible in order to minimize human error. Several manufacturing methods exist that partially or fully eliminate the need to handle the robot during construction. One example is smart composite micro-structures (SCM) which describes a laser micro-machining and lamination process to integrate rigid links and flexure joints into a micro-robot as well as a method for including flexible wiring across actuation joints [6].

Recently there has been an increased interest in the development of miniature robots [7] with robots of all shapes and sizes being developed. One example is a clawed inchworm robot developed by Lee et al [8]. This robot utilizes an electromagnetic oscillatory actuator and three claw like feet to achieve locomotion. This robot

Fig. 1. Monolithic piezoelectric robot

sacrifices mobility by implementing a very simple drive mechanism to reduce the complexity of the design.

Several other examples of miniature robots include, a locust inspired jumping robot developed by Zaitsev et al [9] with an aim to reduce the mass of the robot and increase the energy storage capacity as a means of maximizing the height and distance of the jump. Another example is a miniature robot flying bee-like robot described by Wood et al [10]–[12] and a miniature water strider robot designed by Yan et al [13].

Previous work has involved the design of a three degree of freedom lumped mass model of a leg [14]. This model is used to design the leg in such a way that the first two resonance modes are closely matched. The end result of this work was a prototype miniature hexapod robot with a 3D printed body and end effector. This robot was able to achieve walking speeds up to 350 mm/s when driven at 350 Hz.

This paper presents the design, construction and characterization of the miniature monolithic piezoelectric hexapod robot shown in Fig. 1. The robot will be designed so that the first two resonance modes are closely aligned to achieve an ambulatory motion. The advantage of driving the robot at resonance is that increased deflection and decreased driving voltage can be achieved.

The next section will outline the mechanical design and modeling of the hexapod. Following that, the construction methodology for the robot will be described. The paper will then be concluded with the experimental

The authors are with the Precision Mechatronics Laboratory, School of Electrical Engineering and Computer Science at the University of Newcastle, Callaghan, NSW 2308, AUSTRALIA

¹Shannon.Rios@newcastle.edu.au

²Andrew.Fleming@newcastle.edu.au

³Yuenkuan.Yong@newcastle.edu.au

Fig. 2. Diagram of monolithic leg and end-effector construction

Fig. 3. Dual bipolar series electrical driving configuration

performance results and a summary of future work to be completed.

II. LEG DESIGN

Each leg of the monolithic robot consists of two piezoelectric bimorph benders joined at the tip by an end-effector comprised of a flexure part and a leg part as shown in Fig. 2. In this design the piezoelectric actuators form a significant part of the load bearing structure.

The piezoelectric actuator is comprised of two 0.2 mm thick PZT-5A piezoelectric ceramic elements with a 0.1 mm brass shim separating them. The piezoelectric elements are polled outwardly in a series style configuration and are driven using the bridged bipolar series electrical configuration shown in Fig. 3 which utilizes both the positive and negative electric fields for maximum deflection and force [15]. By driving each bender with a sinusoidal waveform and varying the phase between the two benders, also called ‘step phase’, a wide range of end effector motion paths can be achieved. Of most interest is when the benders are driven with a step phase of 90° to produce a circular motion at the tip of the end effector.

The unique design of the leg results in two resonance modes that are reasonably close together and by altering a small set of variables these resonance modes can be made to overlap. In this design the first resonance mode is dominated by rotation about the z-axis and the second

mode is characterized by rotation about the x-axis as seen in Fig. 2 although the order of these modes may swap depending on the parameters of the leg. By operating at the midpoint between these two modes, the resonant motion of the leg will be a combination of lifting and swinging which produces an ambulatory motion in the robot when driven with an alternating tripod gait.

A. Modeling

Three simplified single degree of freedom lumped mass models were used to design the end-effector of the leg such that the lifting and swinging DoF resonance modes are closely matched. The three models are of the δ_y , θ_x and θ_z degree of freedoms and are referenced to a point at the intersection of the reference x and z axes, as per Fig. 2. The resonance frequency for each DoF is $\omega = \sqrt{\frac{K}{M_e}}$, where ω is the rotational frequency in rads/s, K is the stiffness and M_e is either the M (lumped mass) or I (lumped inertia). The stiffness and lumped masses for each DoF are,

$$K_y = K_f, \quad (1)$$

$$M_y = (M_p + M_f)A^2 + \frac{M_l}{2}, \quad (2)$$

$$K_{\theta_x} = K_{f_x} + 2K_p \left(\frac{P}{2} \right)^2, \quad (3)$$

$$I_x = 2I_{p_x} + I_{f_x} + I_l, \quad (4)$$

$$K_{\theta_z} = K_{f_z}, \quad (5)$$

$$I_z = (I_{p_z} + I_{f_z})B^2 + \frac{I_{l_z}}{2}, \quad (6)$$

where A , B , and P are constants and the subscripts y , f , p , l , θ , x and z refer to the y-axis, flexure, bender, end-effector, rotational degree of freedom, x-axis and z-axis respectively [14].

These models highlight key design parameters that strongly affect stiffness and lumped mass and therefore the resonance modes of the leg. Care must be taken when tuning these parameters to maintain effective deflection and force in the leg, for example, increasing the stiffness of any degree of freedom will have a negative effect on the maximum displacement on the leg. To avoid this, the resonance mode can be tuned by altering the mass distribution or shape of the end-effector. Alternatively small lumped masses can be added to key points on the robot, such as the tip of the benders and end effector, or at the midpoint of the flexure.

The shape of the end-effector, shown in Fig. 4 was designed to change the mass distribution of the leg to bring the lifting and swinging resonance modes closer together. The chosen leg design provided a first and second resonance frequency of 348 Hz and 382 Hz for the swinging and lifting degree of freedoms respectively. These modes can further be tuned by adding small masses to the base and tip of the end-effector and benders once the robot has been constructed. For example, an additional 0.1 g mass at the tip of the end effector should reduce

Fig. 4. Monolithic robot leg end effector. All dimensions are in mm

the difference in swinging and lifting resonance modes to within 1 Hz of each other and reduce the frequency to 189 Hz.

B. Finite element analysis

The monolithic robot was modeled using the FEA tool ANSYS to verify the lumped mass model and analyze the motion of the robot. A modal analysis was completed to determine the resonance modes of the hexapod robot. This analysis showed a swinging mode at approximately 335 Hz and a lifting mode at 373 Hz, shown in Fig 5 and 6 as well as three lower frequency body twisting modes at 239 Hz, 291 Hz and 324 Hz.

A transient analysis was also completed to find the expected motion of the leg during low frequency operation. The legs were driven with a step phase of 90° to produce an elliptical motion with an even mix of lifting and swinging. This analysis showed the step height to be 0.17 mm and the step length to be 0.37 mm. While the lifting degree of freedom is a close match to the lumped mass model, the z-axis displacement is significantly lower.

III. MANUFACTURING PROCESS

A 72 mm square of outwardly poled piezoelectric bimorph from Piezo Systems was used as the material for the monolithic robot. The piezoelectric bimorph is approximately 0.5 mm thick and is comprised of two 0.2 mm piezoelectric layers and one 0.1 mm brass shim joining them together. The leg end-effectors were machined out aluminum using a CNC milling machine.

Several methods for milling the piezoelectric bimorph were trialed before an adequate result was achieved. Initial trails were performed with a simple rotary CNC milling machine, however the PZT material was found to be too hard for the drill bit and excessive heat and wear were observed. Laser ablative cutting of the piezoelectric material was also tested. Despite some initial successes with single layer PZT the addition of a brass shim resulted

Fig. 5. FEA results for the swinging degree of freedom at 335 Hz

Fig. 6. FEA results for the lifting degree of freedom at 373 Hz

in significant damage to the bimorph as a result of heat and warping in the brass layer. The laser cutting method also resulted in slag build up on the underside of the material.

In the end, an ultrasonic milling machine was used to cut the piezoelectric bimorph material. This method proved to be ideal as the ultrasonic machining process produces very little heat and the lateral cutting forces are minimal which reduces stress in the part. The ultrasonic milling machine was able to achieve a high degree of accuracy with reasonably fine features, up to 0.5 mm.

The bimorph PZT by default had a uniform sputtered nickel electrode on both the top and bottom layer. This layer needed to be partially removed to isolate the individual bender elements that comprise each leg. The nickel electrode was etched to remove the unwanted electrode and provide tracks connecting these signals to either end of the robot. After completing the process, the impedance of these tracks was too high and variable to be effective, with resistances from ten to a few hundred Ohms. To improve the conductivity of the tracks silver electrodes were evaporated directly onto the piezoelectric elements, overlapping the existing nickel tracks. All silver tracks had resistance less than 10Ω . The final electrode pattern can be seen in Fig. 7.

Once the electrodes had been etched onto the bimorph monolith the legs were then glued in place using a two part epoxy and a 3-D printed rig to maintain a uniform structure. The total mass of the completed robot weighed approximately 6 g.

Fig. 7. Electrode pattern for monolithic robot

TABLE I
RESONANCE MODES FOR MONOLITHIC LEG

DoF	Lumped Mass	FEA	Experimental Average
δ_y	715 Hz	704 Hz	611 Hz
θ_x	344 Hz	335 Hz	308 Hz
θ_z	382 Hz	373 Hz	326 Hz

IV. PERFORMANCE

A frequency response analysis was performed on the monolithic robot to determine the resonance modes of each leg. This analysis was performed by applying a white noise signal to one piezoelectric element in a leg with the other elements left floating. A Polytec scanning vibrometer was used to generate the input signal and measure the response and a three channel high voltage amplifier was used to amplify the driving signals for the piezoelectric actuator.

The frequency response, shown in Fig. 8, identified several minor resonance modes appearing at approximately 200 Hz, 280 Hz, 380 Hz, 460 Hz and the most significant one at 540 Hz. These modes all involve twisting and bending of the body of the robot, however they have relatively low gain and the additional mass of the control electronics added to the robot will significantly dampen the response. Increasing the stiffness of the body will also reduce the negative effect the body modes have on the operation of the robot by shifting them to a higher frequency.

The frequency response aligns reasonably closely to the lumped mass model with the swinging resonance mode at 308 Hz and the lifting mode at 326 Hz with mode shapes shown in Fig. 9 and 10 respectively for a single leg. The discrepancy between the lumped mass model and the experimental results is most likely due to a combination of the simplified mounting conditions of the lumped mass model and inconsistencies in the size and shape of the end-effectors.

Each leg was tested independently using a single scan point to find the primary resonance modes and check for uniformity across all legs. The resonance modes of each leg were found to be closely matched, with a mean swinging and lifting resonance of 308 Hz and 323 Hz with a spread of 1 Hz and 3 Hz respectively.

Fig. 8. Frequency response of monolithic robot

Fig. 9. 308 Hz mode shape

Fig. 10. 326 Hz mode shape

V. CONCLUSION

A monolithic piezoelectric miniature robot was produced which utilizes the resonance modes to achieve ambulatory locomotion. This paper represents a continuation of previous work describing a lumped mass model used to design the leg such that the first two resonance modes are aligned [14]. The resulting monolithic robot was able to achieve an average resonance mode of 308 Hz and 323 Hz for each leg, with a spread of 1 Hz and 3 Hz respectively.

The monolithic robot has showed significant improvements over previous designs, specifically in the uniformity of the leg performance, as well as the overall mass of the robot. One drawback to this method is less displacement in the y-axis is achieved, due to the non-angled orientation of the legs. This can be improved by splitting the monolith into a left and right hand piece and mounting these at a 30° angle relative to ground to make use of the large displacement along the x-axis in the leg.

The experimental analysis and FEA highlighted a potential problem with some lower frequency resonance modes. These modes involve broad twisting of the body and legs of the robot. Although the gain of these modes are reduced, there is still potential for these modes to interfere with the normal operation of the robot. The simplest way to remove these resonance modes is to increase the stiffness of the body, thus moving the resonance mode to a higher frequency.

Future work will be to miniaturize the drive and control electronics to allow for untethered operation of the monolithic robot. Once this driver is implemented the robot's performance will then be re-characterized based on the ground contact effect. Finally the finished robot will be used as a platform to test various control methodologies for improving performance and navigating unknown environments. Another avenue for research would be to investigate the interaction between the end-effector and various surface types and develop a control strategy that can cope with transitions from smooth to rough surfaces.

REFERENCES

- [1] C. Zhu, "In-pipe robot for inspection and sampling tasks," *Industrial Robot: An International Journal*, vol. 34, no. 1, pp. 39–45, 2007.
- [2] J. Casper and R. R. Murphy, "Human-robot interactions during the robot-assisted urban search and rescue response at the World Trade Center." *IEEE transactions on systems, man, and cybernetics. Part B, Cybernetics : a publication of the IEEE Systems, Man, and Cybernetics Society*, vol. 33, no. 3, pp. 367–85, jan 2003.
- [3] L. Zhang, Q. Huang, Y. Li, J. Gao, H. Li, and L. Wu, "Research and development of throwable miniature reconnaissance robot," *2012 IEEE International Conference on Mechatronics and Automation*, pp. 1254–1259, aug 2012.
- [4] O. Dolghi, K. W. Strabala, T. D. Wortman, M. R. Goede, S. M. Farritor, and D. Oleynikov, "Miniature in vivo robot for laparoendoscopic single-site surgery." *Surgical endoscopy*, vol. 25, no. 10, pp. 3453–8, oct 2011.
- [5] J. a. Paradiso and T. Starner, "Energy scavenging for mobile and wireless electronics," *IEEE Pervasive Computing*, vol. 4, no. 1, pp. 18–27, 2005.
- [6] R. J. Wood, S. Avadhanula, R. Sahai, E. Steltz, and R. S. Fearing, "Microrobot Design Using Fiber Reinforced Composites," *Journal of Mechanical Design*, vol. 130, no. 5, p. 052304, 2008.

- [7] R. Bogue, "Miniature and microrobots: a review of recent developments," *Industrial Robot: An International Journal*, vol. 42, no. 2, pp. 98–102, 2015.
- [8] K.-m. Lee, Y. Kim, J. K. Paik, and B. Shin, "Clawed Miniature Inchworm Robot Driven by Electromagnetic Oscillatory Actuator," *Journal of Bionic Engineering*, vol. 12, no. 4, pp. 519–526, 2015.
- [9] V. Zaitsev, O. Gvirsman, U. B. Hanan, A. Weiss, A. Ayali, and G. Kosa, "A locust-inspired miniature jumping robot," *Bioinspiration & biomimetics*, vol. 10, no. 6, p. 66012, 2015.
- [10] A. L. Desbiens and R. J. Wood, "A wing characterization method for flapping-wing robotic insects," *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 1367–1373, nov 2013.
- [11] R. Wood, R. Nagpal, and G.-Y. Wei, "Flight of the Robobees," *Scientific American*, vol. 308, no. 3, pp. 60–65, feb 2013.
- [12] M. Lok, D. Brooks, R. Wood, and G.-Y. Wei, "Design and analysis of an integrated driver for piezoelectric actuators," *2013 IEEE Energy Conversion Congress and Exposition*, pp. 2684–2691, sep 2013.
- [13] J. H. Yan, X. B. Zhang, J. Zhao, G. F. Liu, H. G. Cai, and Q. M. Pan, "A miniature surface tension-driven robot using spatially elliptical moving legs to mimic a water strider's locomotion," *Bioinspiration & biomimetics*, vol. 10, no. 4, p. 46016, 2015.
- [14] S. A. Rios, A. J. Fleming, and Y. K. Yong, "Design of a two degree of freedom resonant miniature robotic leg," in *Advanced Intelligent Mechatronics (AIM), 2015 IEEE International Conference on*, jul 2015, pp. 318–323.
- [15] S. A. Rios and A. J. Fleming, "A new electrical configuration for improving the range of piezoelectric bimorph benders," *Sensors and Actuators A: Physical*, vol. 224, pp. 106–110, 2015.