Proposed Piezoelectric Energy Harvesting in Mobile Robotic Devices

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***Abstract* – Mobile robots are being utilized increasingly in many applications, which include the exploration of relatively unknown environments including aerial, undersea, volcanic or even alien environments such as the plateaus and deserts of Mars where the Curiosity or Rover robot and others continue to explore. Due to their mobile nature these robots present us with many problems in the area of energy conservation. Mobile robots require more efficient energy saving techniques, due to their inherent self-sustained and self-constrained energy systems. The article is intended to inspire research among the power electronics community on the possibilities of new restorative energy techniques, including the small changes to infrastructure required to enable utilization of these methods. The restorative energy device, described herein, denotes a device that harvests collectable power from the general motion, weight and inclinations of the machine in both factory and remote locations.**

***Keywords* – Energy conversion, Energy harvesting, Mobile robots, Piezoelectricity.**

I. Introduction

Energy conservatism is only one element vital to the success or failure of any mobile robot and from the energy perspective we must look at the main components of the overall methods adopted. The following represents the overall model of the energy ladder consistent with most mobile robotic devices. *Collection / Generation:* this includes all methods of power generators from solar collection photocells to wind generation devices to hydrogen cells to micro pile nuclear devices and such. In many instances these power generation methods are limited, infrequent and susceptible to the variances of nature and resources within a particular environment. *Storage:* though self-explanatory, refers to one of the leading problems facing many modern day devices being the reduction of the overall energy consumption relative to the storage capacity and keeping this in line with generation or collection limits. *Motor / Circuitry Efficiency:* of course the main obstacles remain those motors, circuits, MCU and such which provide locomotion, electronically based analysis and performance of the necessary functions in the mobile robot whatever they may be. *Loss Reduction:* in addition to the use of highly efficient motors it is essential that non-continuous systems where possible, become power independent, just as non-critical systems must shut down when unnecessary. For these non-continuous systems the writer proposes small PZT generator systems utilizing the vibrations of the mobile platform as it performs its continuous tasks. A PZT material, applied to a vibrating structure, results in vibration or strain on the material which results in an output of alternating current which is thereafter converted to DC power for storage in small capacitor banks. The power having been stored will provide power for non-continuous systems when necessary without reliance on main battery energy systems and therefore prolonging the life-cycle of the main batteries. *Collection / Storage of Ancillary Generated Energies:* The re-collecting or harvesting of energy loss is also the subject of must research and involves the production of lesser energies through kinetic or potential energies within the system. It goes without saying that not more energy may be attained than is expended however with a reduction in energy drain and the inclusion of methods to produce minor energies from those expended a longer life-cycle of the mobile robots storage resources may be attained. These methods are most commonly realized in stationary factory robotics where the braking system of a mobile arm for example is utilized to produce generated energies which are fed to other systems or to suitable storage banks [1]. Other methods include breaking powered flywheel generators which also replenish lost energy sources through centrifugal means with high performance magnetic bearings, superior balancing and air-coil generation technologies.

II. Piezo Shock Absorber

In selecting available piezo materials it was first considered to use polymer based PVDF film [2], however PZT ceramic plates became the choice as they were to be embedded within a silicone composite and HF vibration not flexibility was the goal. The generator as depicted in Fig. 1 relies on vibration of the mobile platform's wheel mechanisms including motors, mass of vehicle and the texture of the operating surface. The PZT plates have varied resonant frequencies dependent on size and construction and in the following example have a resonant frequency of 8.5 kHz. At around this frequency the PZT plates in unison generate a maximum output. The advent of mobile factory hybrid robots brings a new level in the need to conserve or harvest existing and previously ignored energy sources. In a controlled environment we may utilize the ability to alter floor texture, where optimum vibration may be achieved to assist in this particular type of energy harvest. For example, if the vehicle's average velocity is 50cm per sec and the floor texture is designed with corrugations of 20 per cm (negligibly smooth surface) then the vibration which may be achieved is 1000Hz as in Fig. 2. As stated the optimum resonant frequency of the PZT plate is of prime importance however any minute flexing of the piezo plates, will produce some voltage. Therefore at various times energy production will be less than optimal. Due to the use of solid, multilayer piezo plates in preference to piezo film or polymer, it is necessary to ensure that the shock absorber generator is not over stressed as the crystalline structures tend to fracture and efficiencies may be lost. There are many variations of the construction theme, these varying for differing robotics platforms and varying piezo devices.

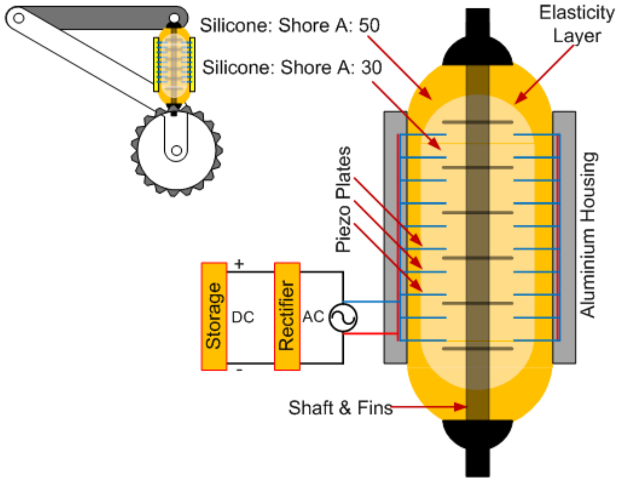

Fig. 1. Proposed piezoelectric shock absorber / generator.

The shaft and fins have been designed to maximize shock absorber vibration evenly to all piezo plates providing a more uniform stress pattern aka voltage output across the system, albeit the absorber is also designed with a goal to minimize upper machine vibration.

III. Counter Intuitive

Any ideal generator with harvesting capabilities by definition must be of a parasitic nature, in other words, not affecting the normal energy consumption of the robot and only extracting energies from ambient sources which are otherwise wasted. Ergo the purposeful creation of additional vibration would at first appear counter intuitive however with the addition and tuning of the resultant vibratory effects more efficient harvesting may be accomplished.

As can be seen Fig. 2 and Fig. 3 offer only two methods of artificial vibration creation which neither affect the normal operation of the robotic platform nor increase the drive power consumption in any appreciable way. The vibration effects are totally absorbed within the harvester device and dependent on the configuration of floor or wheel may reduce robot to floor frictional forces.

IV. Environmental Adaption

In a closed or controlled environment, such as a factory with mobile autonomous robots or as the author has coined, Industrial Service Hybrid Robots (ISH), it is possible to configure machine pathways for adaption to specific needs or in our case, frequencies and alternatively to modify the existing wheel structures to influence again vibration frequencies. An adaption to floor texture as depicted in Fig. 2, or in wheel corrugation as in Fig 3, changes in ISH velocity, varying weight factors or any of these will cause changes in the resultant frequency. Calculation of premium results will be in accordance with the type of PZT element used, the overall performance specifications of the ISH, and RMS output voltage determined by frequency over time.

It is worthy of mention that frictional stresses (wheel to floor) change little in these methods of frequency adjustments with no discernable change in motor energy efficiencies, however it is a consideration necessary in the designing of the device as mentioned in the penultimate paragraph of Section III.

Additionally, in an open or non-static environment the resultant vibration frequencies become random and most commonly fall into the lower frequency range according to the type of terrain traversed, giving rise to heavy spiking and periods of lessened energy production. This problem is alleviated somewhat through even distribution of vibration throughout the harvester device.

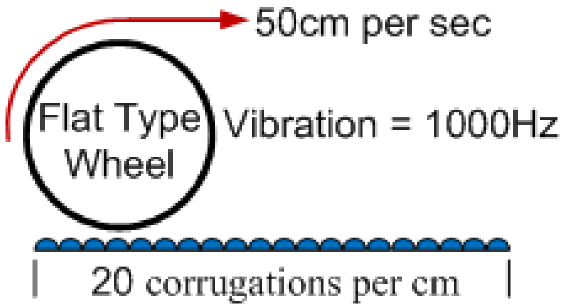

Fig. 2. Vibration frequency increase utilizing floor corrugation.

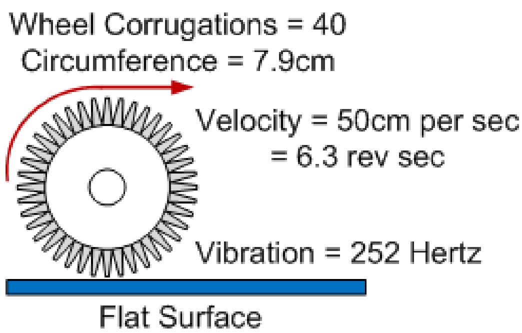

Fig. 3. Vibration frequency reduction utilizing wheel corrugation.

V. Theoretical Design

Piezo film does have some limitations for certain applications because it is a relatively weak electromechanical transmitter when compared to ceramics, particularly at resonance and in low frequency applications. The copolymer film has maximum operating/storage temperatures as high as 135 °C, while PVDF is not recommended for use or storage above 100 °C [3]. Ceramics was selected in that temperature was not a factor but resonance at low and high frequencies forms the main mechanism for operation.

The first pre-emptive prediction of output from the PZT array was based primarily upon the Euler-Bernoulli method for piezoelectric film attached to a beam [4]. A prediction of expected voltage output for Euler-Bernoulli as in Fig. 1

$$V = -\frac{g_{31} M \varphi(1+T)}{b t_a 1 + (\varphi^2 T^2 + 2\varphi(2 + 3T + 2T^2))}, \quad (1)$$

where

g_{31}= piezo stress constant,
M = moment of beam,
b = width of piezo-film,
t_a = thickness,
φ = strain ratio between the beam and piezo,
T = stress on the beam.

Subsequent modelling of the output voltages relating to this method proved to be prohibitively low, approximating 0.35 µW for each PZT which gave a conclusion that the perpendicular and cantilever assembly of our PZT and the encapsulation of the PZTs within a silicone composite would require alternative methods to evaluate voltage output across the 24 PZTs at varying frequency.

The PZT (strain) coefficient prediction may be made, for minimal stress levels, where the surface charge density originates by external stress [5]. The generated charge density is given in (2) as

$$D = \frac{Q}{A} = d_{3n} F_n, n = 1,2,3, \quad (2)$$

where

D = surface charge density,
Q = charge developed,
A = electrode area,
d_{3n} = PTZ coefficient axis stress or strain,
F_n = directional stress applied,
n = mechanical axis: 1 for stretch, 2 for transverse and 3 for thickness.

EMF in the voltage mode is given in (3) as [6]

$$EMF = g_{3n} F_n T_n = 1,2,3, \quad (3)$$

where

g_{3n} = voltage PZT coefficient for axis of applied stress,
T = PZT thickness.

The above represents a guideline only, not the true nature of the proposed method where all PZTs are embedded within a dual layered substrate. Initial estimates indicated high voltage spiking having an overall low RMS which would require step down conversion to around 2 to 4 volts at 10 mA to 30mA for each PVT. Subsequently it was proposed to install 24 PVTs within the apparatus, enabling the use of existing low cost components and achieving reasonable current/voltage outputs for the storage of harvested energies. One underlying factor which will be touched upon in Section VI is that of parasitic capacitance and the most suitable options regarding series or parallel connections of the PVTs.

Due to the propositional nature of this paper and for expedience a small testing device was produced to provide more accurate evaluation vibration transfer through the silicone medium and results to be expected, therefore the model as depicted in Fig. 4 and associated image in Fig. 5. Though not ideal the device provided valuable information regarding the feasibility of the proposal.

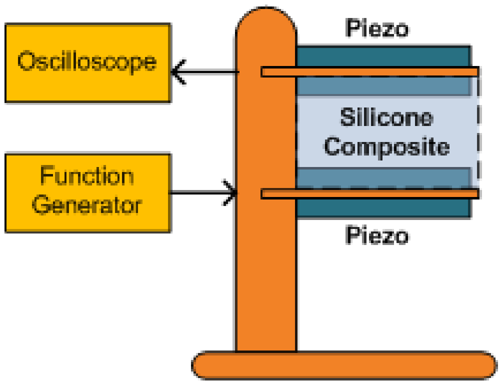

Fig. 4. Model cantilever system – vibration transfer through silicone medium with uniform stress across all PVTs.

The experimental results of various frequencies across the lower PZT and traversing the composite layer are outlined within Fig. 6. The resultant figures are promising yet display a distinct non-linearity. It is surmised that this non-linearity possibly pertains to parasitic capacitance however the scope of this paper does not permit further investigation at this point.

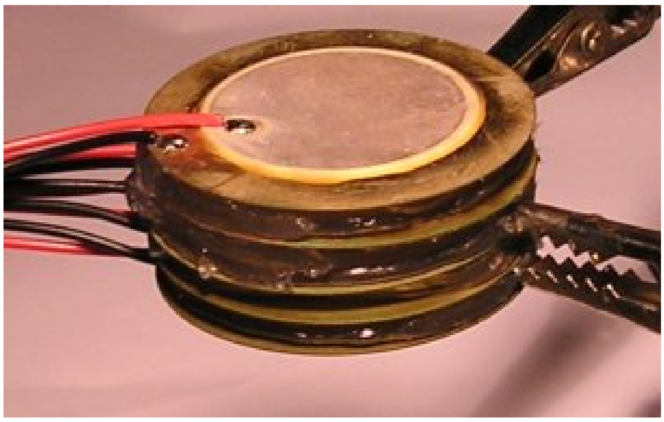

Fig. 5. Cantilever test device.

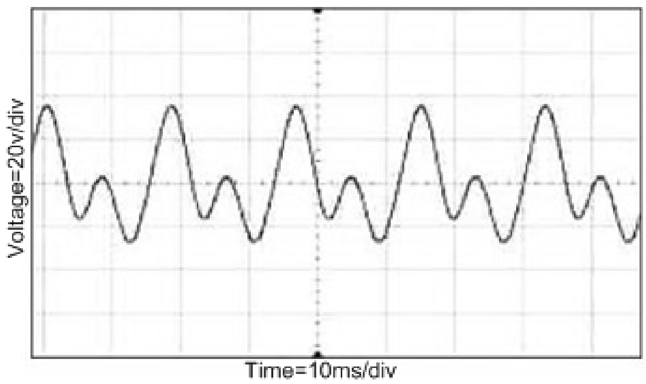

Fig. 6. Laboratory results of cantilever test apparatus.

As indicated in the preliminary laboratory results, harvesting otherwise wasted vibration energy appears quite appropriate using the method proposed, irrespective, there is a non-linearity in the results, possibly due to parasitic capacitance when the PZT elements are connected in series. For harvesting the device would require AC to DC conversion to be as efficient as is attainable in order to facilitate storage of energies in either capacitor banks or ancillary batteries. Figures indicate a V_{rms} no-load output approximating 54.8 volts (per pair of PVTs) and I_{rms} at around 12mA which is quite sufficient for capacitor bank storage. The experiment was performed at a frequency of 50Hz chosen as a starting value for further analysis regarding linearity across a wider range of frequencies. Initial testing was performed resonating the lower PZT to estimate vibratory transfer across subsequent PZT's. The proposed device will contain no less than 24 PZTs arranged and embedded within the transfer medium which provides both shock absorption features and stability for the fragile PZT crystalline structures.

VI. Uniform Stress Across the PZT Elements

Evaluated influential factors that affect the piezoelectric thin film segmented into equal areas, S/n, with uniform stress. The individual piezoelectric elements have the same initial voltages which are proportional to the piezoelectric constant. For simplification, the initial voltage is set to 1 V, and the resulting output voltage is evaluated as the multiplication factor. If the thin film is segmented into elements with stresses that are the same as that of the original thin film, the output voltage, V_n, is equal to the multiplication factor, M, which is expressed as follows in (4)

$$M = \sum j \sum k K_{jk} , \quad (4)$$

$$K = (1 + G C_p^{-1} C)^{-1} . \quad (5)$$

Assuming a parasitic capacitance-free circuit, the output voltage should be proportional to the number of connections. The expected output voltage indicated by a series connection of PZT is ideally the simple summation of output voltages produced by all elements. The influential factor of the parasitic capacitance can be defined by the ratio of the obtained output voltage to the summation of the output voltage from all elements. For example, the influential factor is 0.5 for a 27-element connection with a thickness of 5 µm [7].

VII. Prototype Construction

The image in Fig. 7 gives an idea of the construct of the prototype, being a four wheeled chassis with energy harvesting suspension to all wheels.

The prototype will also experiment with the use of 4 WD PWM control utilizing weight, gravity, direction and centre of gravity to individually control the energy consumption to each drive wheel through various sensing techniques, further maximising the efficiencies of the energy harvesting suspension. This however is beyond the scope of this paper.

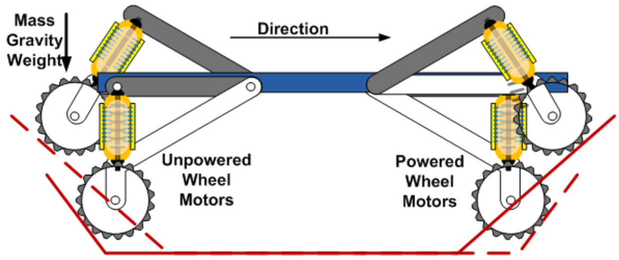

Fig. 7. Proposed four wheeled prototype image.

VIII. Conclusion

The results of the testing have proved more than satisfactory and are indicative that although more intensive research is required, the system is worthy of prototype construction. Furthermore the results appearing in Fig. 6 is the main indicator of the potential of the method. Completed construction of the prototype will allow accurate definitions of the mathematical allowances needed for the correct evaluation of PZTs in the proposed application. Future work will continue with focus on obtaining an efficient and inexpensive energy harvesting system for ISH Robots and autonomous robots in open environments.

References

[1] Xu Jiakai, Yang Jianqiang and Gao Jian, An integrated kinetic energy recovery system for peak power transfer in 3-DOF mobile crane robot, IEEE/SICE International Symposium. pp. 330–335, (2011).

[2] Kornbluh, R., “Compact and Lightweight Energy Conversion using Electrostrictive Polymers” in M.F. Rose,Ed., Prospector IX: Human-Powered Systems Technologies, Space Power Institute, Auburn University, AL., November1997, pp. 313-329.

[3] Piezo Film Sensors Technical Manual – Tufts University. www.tufts.edu/programs/mma/emid/piezo.pdf

[4] Eggborn, T. Analytical Models to Predict Power Harvesting with Piezoelectric Materials. MSc Thesis. Virginia Polytechnic and State University, (2003).

[5] Monika Jain, Usha Tiwari and Mohit Gupta, Mobile Charger Via Walk. IMPACT– (2011)

[6] Piezo Film Sensors Technical Manual, Meas. Specialties, Inc., Norristown, PA, 1999

[7] Kensuke Kanda, Takashi Saito, Yuki Iga, Kohei Higuchi and Kazusuke Maenaka. Influence of Parasitic Capacitance on Output Voltage for Series-Connected Thin-Film Piezoelectric Devices. Sensors (2012), 16673-16684. http://www.mdpi.com/1424-8220/12/12/16673/htm

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