Spatiotemporal Assignment of Energy Harvesters on a Self-Sustaining Medical Shoe

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Abstract— **We present a new method for spatiotemporal assignment and scheduling of energy harvesters on a medical shoe tasked with measuring gait diagnostics. While prior work exists on the application of dielectric elastomers (DEs) for energy scavenging on shoes, current literature does not address the issues of placement and timing of these harvesters, nor does it address integration into existing sensing systems. We solve these issues and present a self-sustaining medical shoe that harvests energy from human ambulation while simultaneously measuring gait characteristics most relevant to medical diagnosis.**

I. INTRODUCTION

Wireless sensor networks have become a powerful and practical means for extracting information in a myriad of environments, ultimately extending the reach of data collection to gain new and deeper insights into these domains. Most notably, the application of wireless sensor networks to the human body has helped foster the growth of the wireless health community. Medical professionals are now able to extend the reach of ailment and disease diagnosis beyond the walls of hospitals by gathering medical measurements during the day to day routines of their patients.

While small form, low power, and high accuracy are some of the more important design considerations for medical sensing devices, high accuracy can often lead to large, complex, and power hungry designs. However, most medical sensing devices are inherently mobile, such as walking canes and medical shoes, and should be designed with low energy and low power features as the foremost design considerations [1] [2].

While traditional approaches to optimizing power demands attempt to minimize energy requirements, we present a new procedure for medical health devices that employs energy harvesting techniques. Instead of a top-down approach that attempts to minimize the design to fit the energy restrictions of the power system, we propose to switch the power system to a sustainable energy source. The focus of this investigation is on creating a sustainable medical wireless sensing device, specifically, a medical shoe fitted with sensors that measure gait characteristics and abnormalities. We present a sustainable design via spatiotemporal assignment of harvesters that extracts maximal energy determined by the gait and pressure spatiotemporal distribution of the patient.

II. RELATED WORK

The emergence of wireless sensor networks has paved the way for new methods for human monitoring through a variety of applications including gait analysis, sleep observation, and emotional health monitoring [2] [3] [4]. However, some wireless health devices, such as a medical shoe, must be accompanied by a mobile power source. Even so, some wearable sensing systems are still designed with power hungry sensors and large arrays. When in operation these systems can drain their power sources quickly, often requiring frequent battery replacements or recharges, ultimately deterring patient adoption of such wearable sensing systems.

Traditional approaches to minimize the impact these power hungry devices have on patient routine range from cost minimization to energy reduction in the hopes of creating cheaper, smaller form, and lower energy devices [5] [6] [7] [8] [9] [10]. Energy reduction in particular has been accomplished through a multitude of techniques, including hardware design, sensor array reduction, and subsampling [11] [12] [13] [14].

The topic of energy harvesting encompasses a wide range of mechanisms including solar capture techniques, electrostatic and piezoelectric transduction, and thermoelectric harvesting, among others [15] [16] [17]. In the context of human energy scavenging, walking might be the most obvious source of harvestable energy. Shoe harvesting designs date back to as far as the 1920's, however these systems were much too bulky for practical human wear [18]. More recent solutions have utilized piezoelectrics and electromagnetic generators for energy conversion, however the latter remains too bulky for comfortable use and while the former has been one of the driving materials behind the development of energy scavenging shoes, it's energy density remains low.

Most recently, dielectric elastomers (DEs) have emerged as the premier class of material capable of energy densities ranging from 5 to 40 times the densities of piezoelectrics [19]. Similar to piezoelectrics, they posses the ability to behave as energy transducers, actuators and sensors. While piezoelectrics create an electric field when flexed due to their internal molecular structure, DEs effectively change in capacitance when strained. Thus an electric field must be applied to the device during strain and extracted after the strain has been removed in order to achieve net energy output. We discuss the intricacies of this process in Section IV-A.

III. MOTIVATION

While DEs are a relatively new material, they have already proven to provide higher energy densities than other small

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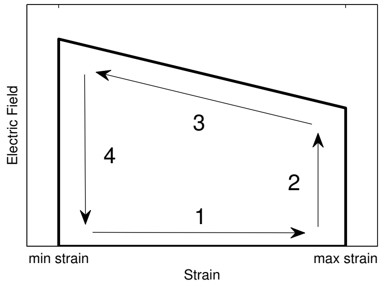


Fig. 1: Typical DE energy harvesting cycle. (1) Stress is applied to the DE increasing its strain. (2) The loading charge is applied at the maximal achieved strain, thus creating an electric field across the DE. (3) The stress is removed from the DE and its strain is reduced. (4) The electrical energy is harvested from the DE; the energy is equivalent to the area inside the cycle. The slope of step 3 is a result of the fact that this model assumes a constant charge through relaxation.

form transducers capable of being mounted on wearable sensing systems. Their ability to be utilized for shoe energy scavenging has been demonstrated, however integration into existing medical systems has not yet been discussed. Meanwhile, the wireless health community continues to rely on traditional batteries for power. It is generally agreed upon that energy harvesting is an import and necessary challenge and opportunity in the wireless health domain [20].

Thus far, no combination of harvesters and sensors has been presented using a medical device. Independently, medical shoes and shoe energy harvesting have become popular topics, however no papers present successful utilization of DEs for shoe energy harvesting while simultaneously sensing medical diagnostics.

Traditional techniques for shoe energy scavenging employ piezoelectric or electromagnetic technology. DEs promise to replace these technologies with superior energy density, low mechanical complexity, and low cost [19] [21]. This increased energy density enables the use of DEs for a self-sustaining shoe, eliminating battery replacement and wall charging altogether by allowing for near-continuous battery charging at each human step.

While DEs have and continue to demonstrate superb energy harvesting capabilities, the nature of the DE, as will be discussed in Section IV-A, requires precise timing information in order to operate at maximum capacity. When designing a self-sustaining shoe, not only is the placement of the harvesters paramount in maximal energy scavenging, but so is timing. A DE requires a charge to be applied at its maximal strain in order to be harvested for maximal energy gains after relaxation. Thus, we propose to use the sensing information in medical shoes to time the harvesters while simultaneously measuring medical diagnostics.

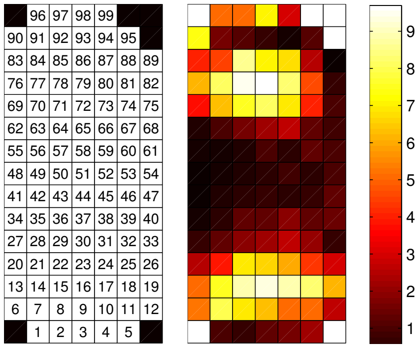
IV. PRELIMINARIES

A. Dielectric Elastomers

DEs are deformable polymer films built from a variety of materials, the most common of which include acrylics and silicones due to their high electric permittivity (ϵ_r) and elasticity. Their relatively high elastic energy density means they can store more energy when deformed for the same amount of material, yielding less bulky and more productive transducers [19].

When a DE is strained, the internal structure of the material changes in capacitance following Equation 1, where λ is the area expansion factor. This change in capacitance allows for net energy harvesting outlined in Figure 1.

Thus, employing DEs in a shoe energy harvesting system is not as simple as placing them at the highest pressure points along the sole. Equally important is the charge timing of the DEs. While they are superb harvesters, they are most easily applied in environments with constant frequency pulsations, such as the vibrations found in machinery, bridges and buildings, where charge timing is easily predicted. While the human gait is fairly constant, it has a broad spectrum. Thus, charging and extracting energy from a shoe-mounted DE requires precise timing prediction to determine when it will reach its maximum pressure during ambulation.



(a) (b)

Fig. 2: Average optimal energy output (mJ) per step at each harvester location. The applied load charge is the same at each harvester but applied at the optimal timing specific to each harvester while remaining constant across steps.

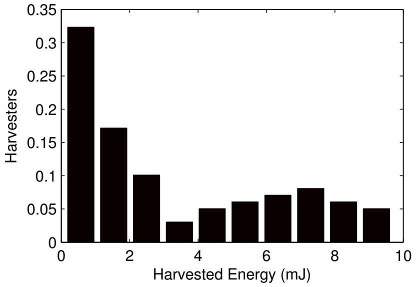


Fig. 3: Distribution of average optimal energy output per step across all potential harvester locations on the pedar mapping assuming the load charge is applied at the optimal timing specific to each harvester.

B. Harvester Simulation

We apply the detailed model derived by Jean-Mistral et al. to compute the harvested energy per step on our medical shoe system [22]. We simulate a 9.5mm × 9.5mm VBH4910

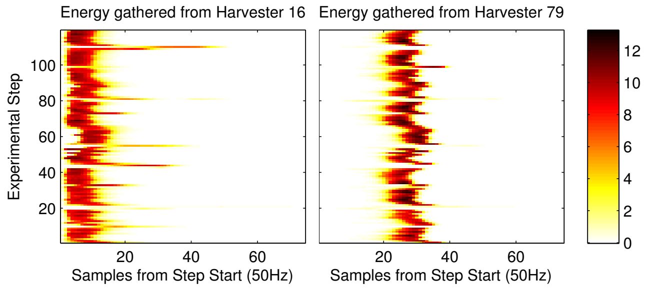


Fig. 4: Potential energy harvesting points for harvesters 16 and 79. Assuming the top three harvesters are installed and timed optimally, and the average ambulation frequency is 2Hz, each shoe would produce about 34mW.

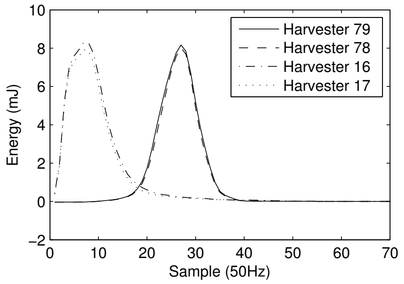


Fig. 5: Top harvester average energy distributions given that the charge is applied to the DE at the specified sample time and the energy is harvested at the step end.

acrylic DE manufactured by 3M with a single 1mm thick DE layer [23]. The energy generated by the dielectric elastomer is calculated using Equation 2. Ultimately we take into account electrical energy losses and mechanical losses and compute the harvested energy via equation 3.

$$C_\lambda = \frac{\epsilon_0 \epsilon_r \lambda^2 A}{d/\lambda^2} \tag{1}$$

$$\Delta E_{DEG} = \frac{Q^2}{2C_1}\left(\frac{1}{\lambda^4_{final}} - \frac{1}{\lambda^4_{init}}\right) \tag{2}$$

$$E_{harv} = \Delta E_{DEG} - E_{loss_{elec}} - E_{loss_{mech}} \tag{3}$$

C. Medical Shoe

Our medical shoe consists of ninety-nine pressure sensors distributed about the sole of the foot, a processing unit, flash memory, a radio, and an ADC. The passive resistive pressure sensors are located along the sole according to the Pedar plantar mapping [24] and numbered in Figure 2a.

Wendt et al. has shown that gait measurements sufficient for medical diagnosis can be predicted by employing just a handful of sensors from the original array of ninety-nine [25] [26]. A single global sensor is all that is necessary to capture the start and end times of a human step. In this paper we also show that the single global sensor is adequate to predict optimal temporal assignment of harvesters for maximal energy harvesting.

V. HARVESTER SPATIOTEMPORAL ASSIGNMENT

The fine level of detail in pressure distribution provided by the medical shoe helps determine which locations are most optimal for energy harvesting. However, harvester placement not only requires spatial arrangement but also temporal assignment due to the nature of the DE energy harvesting cycle. While Figure 2b shows that harvesters 16, 78, and 79 have the highest potential energy, if the maximum strain timing cannot be predicted with sufficient accuracy, then the energy produced by these harvesters will be suboptimal.

Thus, we provide a solution for both spatial placement and temporal assignment of DE harvesters on the medical shoe. We accomplish this via energy profile prediction using the global sensor. As previously explained in Section IV-C, the global sensor is tasked with measuring the start and end times of human steps. We examine the relationship between global sensor-samples and potential harvester-samples and generate models of each harvester energy profile given a global sensor-sample value relative to the start of the step. We compute regression models between subsequent global sensor-samples and measure their ability to predict harvester energy profiles. We choose a minimal set of global sensor-samples for prediction that maximize harvested energy. This ultimately comprises a complete mapping of global sensor-sample to harvester energy profiles and ultimately determines both the spatial placement of harvesters and their temporal assignment as determined by the best global sensor-sample predictors.

This procedure can be executed before or after sensor placement. If performed after, the harvesters are chosen from the remaining lots on the sole of the shoe. If performed before, upon choosing the physical placement of a subset of harvesters, the remaining vacant lots can be filled with medical sensors. If, however, cost is an important factor in design, the number of sensors can still be reduced using the existing sensor selection techniques mentioned previously.

VI. RESULTS

Figure 2b depicts the distribution of average energy gains across the foot given that the charge is applied at the optimal time per harvester. Figure 3 shows that about 40% of harvesters are capable of producing an average of 3mJ or more per step.

We find that the global sensor-samples have significant correlation to the top harvester energy profiles depicted in Figure 4 and 5. After training the global sensor-sample predictors for harvester energy profile prediction, we choose a covering set of global sensor-samples that predict a number of harvesters for maximal energy gains.

The best global sensor-sample predictors for each of the potential harvesters are able to harvest 93% of the harvesters within 72% to 97% of their maximum potential. Even if the timing prediction is off by one to a few samples, 90% of steps are harvested within 1mJ of optimum for the top harvester, as depicted in Figure 6.

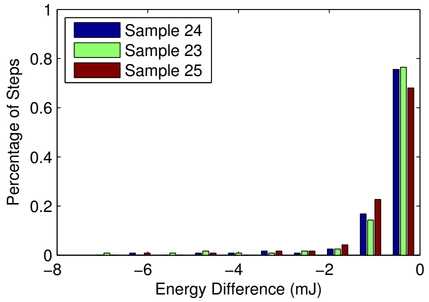
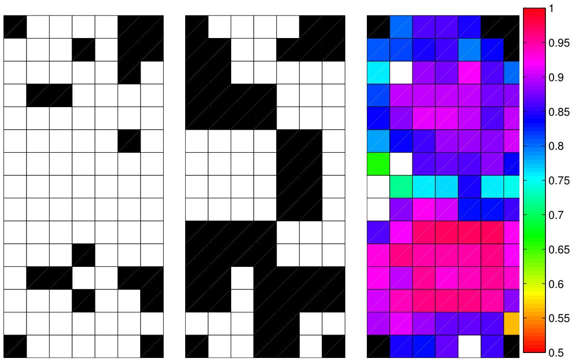


Fig. 6: Distributions of the difference in harvested energy from the optimal potential harvested energy using the labeled global sensor predictors on harvester 79. For about 90% of all steps, each of the top three sensor-sample predictors are able to harvest within 1mJ of optimum.



(a) (b) (c)

Fig. 7: (a, b) Minimum subset of sensors capable of measuring gait characteristics necessary for medical diagnosis [25] [26]. (c) Average harvested energy as a percentage of the optimal energy in Figure 2b. Energy is harvested when the predicted energy profile of each harvester (as predicted by the global sensor) is at maximum.

Figure 7c depicts results from our global sensor-sample energy profile prediction algorithm along with previous results for sensor selection for medical diagnostics. Upon assigning the sensors from either Figure 7a or 7b, covering the remainder of the sole with DE harvesters and predicted using the global sensor easily powers the entire medical shoe at a human ambulation rate of 2Hz.

VII. CONCLUSION

With the continuing development of wireless medical sensing devices, it has become imperative that we develop new design techniques that acknowledge energy as the premier design consideration. While much attention has been given to methods for reducing power demands of wireless wearable sensing devices, incorporating the human body for power generation is still unsolved. Thus, we have presented a method for application of energy harvesters to a wireless medical sensing device.

Specifically, we have presented a new procedure for spatiotemporal assignment of DE energy harvesters for a self-sustaining medical shoe. Our approach utilizes the global sensor to predict the energy profiles of harvesters along the sole of the shoe and subsequently install harvesters in those locations and, in real-time, predict the optimal timing of the various stages of the DE energy harvesting cycle. Our technique is capable of harvesting enough energy to power the medical shoe at an ambulation rate of 2Hz.

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