

Modeling Energy Harvesting Sensors using Accelerometer in Body Sensor Networks

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ABSTRACT

This paper presents an experimental modeling framework for energy harvesting sensors in Body Sensor Networks (BSN). Most of BSN applications assume that the sensor nodes have infinite and continuous source of energy. But in reality, this may not be true, especially for the implanted sensors. Instead, the energy for the implanted BSN sensors is likely to come from harvested energy sources such as piezoelectric, magnetic, and thermo-electric generators. In this paper we will explore on-body sensors energy harvesting model using acceleration which is getting a lot of attention in the research community. Recharging batteries with harvested energy could not only extend battery life, but may also dissolve the conventional meaning of network life time. While the energy-harvesting sources can vary widely, we will focus primarily on harvesting using vibration of piezoelectric sensors. Since the piezoelectric energy harvesting depends on movements, the amount of energy harvested at a specific on-body sensor node will depend on the movement pattern of the body part that the node is attached to. As a result, the specific energy generation profile at the BSN nodes does depend on the postural body movement patterns over time.

Keywords

Body Sensor Networks, Energy Harvesting Model, Sensor Accelerometer, Postural Body Movement, Sensor Placement.

1. INTRODUCTION

Body Sensor Network (BSN) [1] consists of a number of small wireless sensors that are expertly placed or implanted on a human's body. Generally, a BSN can be used to monitor different body vital signs in real-time, providing response to the service provider. This kind of monitoring is enabling the service provider for diagnostic process of many patients with chronic conditions, or during the recovery improvement from a disease or surgery operation. Data communication between body sensors can be multi-point-to-point or point-to-point. While distributed detection of an athlete's posture would require point-to-point packet exchange across various on-body sensors, applications such as monitoring vital signs, as shown in Figure 1, will require all body-mounted and/or implanted sensors [2] to route data *multi-point-to-point* to a sink node, which in turn can process and relay the

information wirelessly to an out-of-body server. Data transaction can be also real-time or non-real-time. While patient monitoring type of applications would require real-time data aggregation, monitoring an athlete's physiological data can be collected offline for post-processing and analysis purposes. The energy harvesting model in this paper caters the real-time and non-real-time classes of on-body applications.

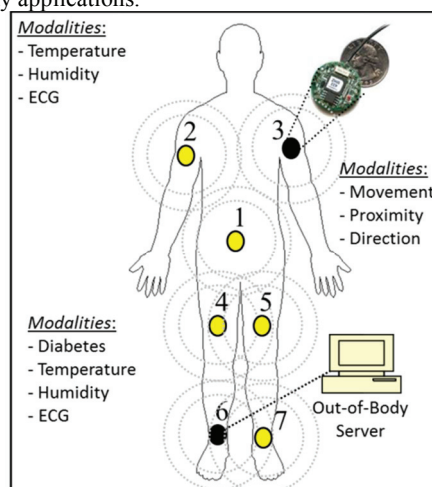


Figure 1: Wireless Body Sensor Network

Generally, wireless sensors are limited in resources of power, especially when we are talking about implanted or wearable sensors in BSN. To solve the limitation of power, in this paper we model on-body energy harvesting wireless sensor in the presence of topological movement caused due to postural body movements. Short transmission range is a common constraint for low-power RF transceivers designed for embedded applications with limited energy [3], often supplied by harvested operations [4]. Such situations are particularly pertinent for implantable body sensors. In the literature, the transceiver range of such sensors is considered ultra-low with range of 0-1m [5] with corresponding transmission powers vary between 0.75mW to 6mW, which are within a range that can be handled with body movements and common harvesting techniques such as piezoelectric generation.

Energy harvesting, also known as power harvesting or energy scavenging is a process by which energy is derived from external sources, such as, solar power [6], thermal energy [7], wind energy [8], salinity gradients [9], and kinetic energy [10], captured, and stored for small, wireless autonomous devices, like those used in wearable electronics and wireless sensor networks [11]. Energy harvesters provide a very small amount of power for low-energy electronics. While the input fuel to some large-scale generation costs money (oil, coal, etc.), the energy source for energy harvesters is present as ambient background and is free. For example, temperature gradients exist from the operation of a combustion engine and in urban areas; there is a large amount of

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BODYNETS 2013, September 30-October 02, Boston, United States

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DOI 10.4108/icst.bodynets.2013.253588

electromagnetic energy in the environment because of radio and television broadcasting. In this paper, the source of external energy is coming from the body movement of the piezoelectric cell in the wireless sensor.

In this paper we assume the wireless sensor is constructed using a piezoelectric cell. First, we have developed a piezoelectric generator model that harvests mechanical vibrations energy available on the wearable sensor. Second, we have experimentally evaluated the proposed model using BSN. Finally, we have studied that impact of body postural movement and sensor location on the amount of harvested energy. The novelty of this approach includes: 1) experimental evaluation of the proposed framework in a practical prototype BSN system, and 2) development of detailed energy harvesting model that can be useful for pre-deployment system dimensioning, planning, and what-if analysis of real body sensor networks.

2. RELATED WORK

The main limitation of sensor networks is finite of the battery capacity nodes, which leads to finite network lifetime, especially in BSN. Sensor nodes could use larger capacity battery, but that will increase the sensor node cost, size and weight. It is possible reducing the hardware of the nodes by reducing the processor and radio powers, but that will reduce the capability of monitoring in many applications and will reduce the transmission range.

There are many proposed techniques to increase the power of the battery of the sensor nodes and then to increase the network lifetime. Examples of these techniques include MAC protocols [12], data-storage power aware [13], energy-aware data routing [14], placement of the nodes [15], system architectures [16], efficient duty cycle techniques [17]. All above techniques maximize the network life time, but still the lifetime of the sensor node is limited. Therefore, a continuous and periodic source of energy is needed by having an energy harvesting technique.

In literature, many energy harvesting techniques have been studied. Some of these techniques depend on the surrounding environment as source of energy [6], [7], [9], [10], which are not applicable for BSN. Some other techniques depend on the human power, like harvested energy from the body movements of the human [18]. These techniques rely on standalone copious interactive devices in shoe with very limit modalities. Authors in [8] harvest energy using wind by using turbines and rotors to convert the motion into electrical energy. Many forms of solar harvesting sensor nodes have been presented [6]. The implementations of solar energy harvesting are different. Most of these implementations depend on the axes of the characteristics of solar panels, complexity of the design, battery and the capacity of the battery.

Energy-aware for routing protocols using energy harvesting sensors have recently been reported in the literature [19]. A number of these papers focus mainly on energy aware routing algorithm for target region monitoring. A packet in opportunistic routing [20] is forwarded to a set of neighbors with different probabilities to increase the likelihood of receiving the packet. The energy drainage due to retransmissions of the packet is reduced in this routing mechanism by sending the packet to multiple receivers at once, and based on the outcome, the actual next hop is chosen.

All the above works did not propose any framework for energy harvesting sensor in BSN and based on the body movement and acceleration as we are going to do in this paper. On the other hand, none of these works studied energy harvesting sensor as part of energy-aware applications in BSN and as reported in [3], [21] which will get a lot of attention in the research community.

3. CHARACTERIZATION OF BSN

To model energy harvesting sensor in BSN we have implemented a working BSN prototype system. This section describes the BSN prototype and its application for experimental body movement and energy harvesting sensor characterization with varying body postural positions.

A Body Sensor Network (BSN) is constructed by attaching seven sensor nodes on the human subject. In this prototype we have used seven sensor nodes (one in the waist, two in lower ankle, two in middle thigh and two in upper-arms). Figure 1 shows the BSN prototype that we have used. Each wearable sensor node is constructed by a 900MHz Mica2Dot MOTE (running TinyOS operating system), with Chipcon's SmartRF CC1000 radio chip (chipcon.com), and the sensor card MTS510 with dual-axis accelerometer (in x-axis and y-axis) from Crossbow Inc. (www.xbow.com). The Mica2Dot nodes run from a 570mAH button cell with a total sensor weight of approximately 10 grams. The default CSMA MAC protocol is used with a data rate of 19.2kbps.

The accelerometer outputs in x and y axes provided by MTS510 sensor card are characterized to model the instant piezoelectric displacement in x and y directions, as we will discuss in *Section 4*. Via software adjustments of the CC1000's transmission power, the transmission range is set to be in between 10-25 inches. By doing so, we are able to emulate the ultra-low power with transmission range for the embedded transceivers [4] as reported in the literature. Note that the variation of the range is caused due to the variability in antenna orientation, clothing, and other on-body RF attenuation characteristics.

The sensors form a mesh topology with one or multiple simultaneous network partitions. The topology and the number of partitions change dynamically based on the postural positions of the subject individuals. At the same, the postural of the subject individual will dynamically harvest energy in the corresponding attached sensor node, as we will see in *Section 4*. All experiments in this paper correspond to multi-point-to-point data aggregation in which data from all other nodes are sent to node-6 (see Figure 1) [21], which is designated as the on-body sink node. This node collects raw data, and sends processed results or events to an out-of-body server using a wireless link. This external link is created between the on-body sink node and to an out-of-body Mica2Dot radio node connected to a Windows PC through a custom-built serial interface, running RS232 protocol.

Experiments were carried out for observing the impacts of postural mobility on the accelerometer readings of the sensor. A human subject, fitted with seven sensors, was asked to follow a pre-determined sequence of postures (SIT, SIT-RECLINING, LYING-DOWN, STAND, WALK and RUN), each lasting for 20 sec. The accelerometer outputs of four sensors (1, 3, 5 and 7) during such an experiment are shown in Figure 3-a for each sensor, as we will discuss in *Section 5*. These sensors correspond to the waist, arm, thigh and ankle sensors, respectively. In the figure, m_x and m_y are the x - and y -axes readings [22] in milli-g (1 mg is 9.81 mm/s^2) from all four sensor nodes, while a human subject was following a controlled 20-postures sequence as shown along the horizontal axis of the figure. Each posture slot in this experiment had lasted for approximately 20 seconds. A sampling rate of 20 Hz has been used for obtaining reading from the accelerometers. The accelerometer readings in Figure 3 from the nodes are periodically sent by all sensors to the out-of-body server (in Figure 1) using the full transmission power of the Chipcon's CC1000 radio.

As shown in the Figure 3-a, the change of accelerometer readings increase for the activity-intensive postures such as WLK

and RUN compared to low-activity postures such as SIT, SIT-RECLINING, LYING-DOWN and STAND. In fact the readings for SIT, SIT-RECLINING, LYING-DOWN and STAND are almost the same due to the absence of any major physical activity in these postures. The same observation can be made for all sensors, but with different rate.

The second observation that can be made from Figure 3-a is that the variations of the accelerometer readings of the four sensors are varied according to the attached position of the body. As shown in the figure, the variation of the accelerometer readings of sensors 5 and 7 (the thigh and ankle) are significantly higher than the variation readings of other two sensors and according to the proposed posture. That mean, for a given posture or physical activity and attached sensor node, the accelerometer readings are varied. Such variation in accelerometer readings can be used for energy harvesting as in piezoelectric generator [23], [24].

4. MODELING ENERGY HARVESTING

The objective of this section is to model BSN energy harvesting mechanism that is similar to the piezoelectric generator. The accelerometer sensor in the proposed sensor is assumed to have similar impact of the piezoelectric cell and as in the mechanical vibration. Then, the harvested energy in these sensors can be used for data sensing and packet routing in BSNs.

According to the technique reported in [23], [24] the power that can be harvested using a piezoelectric cell is given by:

$$P = \frac{ds^2}{2} \cdot \frac{M^2 \cdot \alpha^2 \cdot R \cdot \omega^4}{((\alpha^2 \cdot R + D)^2 + (R \cdot C \cdot D \cdot \omega)^2)} \quad (1)$$

where M is the damper mass, α is the force factor, D is the damper factor, ω is the sampling frequency, R is the piezoelectric circuit resistor, C is the piezoelectric circuit capacitance and ds is the piezoelectric cell displacement due to sensor movement.

With optimal load resistor R and very small α due to adequately electromechanically joined assembly of this prototype, the maximum power that can be harvested using this structure is given by:

$$P = \frac{ds^2 \cdot M^2 \cdot \omega^2 \cdot \alpha^2}{4 \cdot D^2 \cdot C} \quad (2)$$

The above model can be used in the piezoelectric sensor in our prototype system illustrated in Section 3 for the purpose of harvesting energy. For given M , α , D , ω , R , C values as reported in [23], [24], at any given point of time, the accelerometer outputs in x and y axes provided by MTS510 sensor card can be used to model the piezoelectric displacement in x and y directions. Then, we can use this instant piezoelectric displacement as an input to the energy harvesting model presented in Eqns. 2 to compute the instantaneous harvested energy.

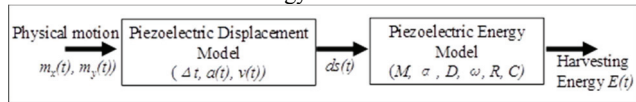


Figure 2: Piezoelectric energy harvesting model

Figure 2 demonstrates the structure of the piezoelectric energy harvesting model that we will use as the energy source at each sensor node. The first part of the model demonstrates the piezoelectric displacement driven from the accelerometer measurements (m_x and m_y) in x and y directions. Then the overall displacement ds , output from the displacement model, is used as an input to the energy model presented in Eqn. 2 to compute the harvested power and then the harvesting E as shown in Figure 3.

For given M , α , D , ω , R , C and piezoelectric cell displacement ds , the harvested power presented in Eqn. 2 can be simplified as:

$$P = K \cdot ds^2 \quad (3)$$

where $K = \frac{M^2 \cdot \omega^2 \cdot \alpha^2}{4 \cdot D^2 \cdot C}$ is the harvesting power constant. In order to compute the instantaneous harvested energy E at time t from Eqn. 3, the harvesting power should be computed during a unit of time Δt , as shown in Figure 2. For given M , α , D , ω , R , C , the amount of energy $E(t)$ that can be harvested during $t - \Delta t$ to t , can be written as:

$$E(t) = K \cdot ds(t)^2 \cdot \Delta t \quad (4)$$

The interval Δt also represents the time duration between two successive accelerometer measurement points. The quantity $ds(t)$ in the model represents the piezoelectric displacement during the time slot $t - \Delta t$ to t . The piezoelectric displacement $ds(t)$ is given by:

$$ds(t) = \sqrt{x(t)^2 + y(t)^2} \quad (5)$$

where, $x(t)$ and $y(t)$ are the piezoelectric displacements during $t - \Delta t$ to t in x and y directions, respectively.

To compute $x(t)$ and $y(t)$ displacements, the following displacement model can be used. For a given $m_x(t)$ and $m_y(t)$ accelerometer measurements, the actual piezoelectric accelerations $a_x(t)$ and $a_y(t)$ in x and y directions can be respectively computed as:

$$a_x(t) = m_x(t) - \frac{1}{U} \cdot \sum_{i=1}^U m_x \cdot (t - \Delta t \cdot i) \quad (6.a)$$

$$a_y(t) = m_y(t) - \frac{1}{U} \cdot \sum_{i=1}^U m_y \cdot (t - \Delta t \cdot i) \quad (6.b)$$

where $\frac{1}{U} \cdot \sum_{i=1}^U m \cdot (t - \Delta t \cdot i)$ part in the equation illustrates the moving average of the accelerometers during a window size of U . The rationale behind subtracting this moving average value from the current accelerometer are to remove the gravitational acceleration value from the piezoelectric displacement computation, and to see the effect of the current movement on the piezoelectric displacement by using a measured acceleration and applying the motion equations. In the following displacement process computation, we will notice same equations for both x and y directions are illustrated for displacement computation.

To decide the static points, where the velocity of the piezoelectric is zero, we propose to use the following condition, $abs(a_x(t)) \leq 0.5$ and $abs(a_x(t-\Delta t)) \leq 0.5$, which means the current and the previous acceleration values are less than or equal to the value of 0.5 mm/s^2 according to Eqn. 6. If the above condition is not satisfied, the following equation from the motion equations is used to compute the velocity at time t in x and y directions:

$$v_x(t) = v_x(t - \Delta t) + \frac{a_x(t-\Delta t) + a_x(t)}{2} \cdot \Delta t \quad (7.a)$$

$$v_y(t) = v_y(t - \Delta t) + \frac{a_y(t-\Delta t) + a_y(t)}{2} \cdot \Delta t \quad (7.b)$$

where the term $\frac{a_x(t-\Delta t) + a_x(t)}{2}$ represents the average acceleration in $t - \Delta t$ and t interval. Then the piezoelectric displacement in x and y direction and at time t is computed from the motion equations as:

$$x(t) = v_x(t - \Delta t) \cdot \Delta t + \frac{1}{4} \cdot (a_x(t - \Delta t) + a_x(t)) \cdot \Delta t^2 \quad (8.a)$$

$$y(t) = v_y(t - \Delta t) \cdot \Delta t + \frac{1}{4} \cdot (a_y(t - \Delta t) + a_y(t)) \cdot \Delta t^2 \quad (8.b)$$

5. ENERGY HARVESTING RESULTS

The BSN is constructed, as illustrated in the prototype system in Section 3, by mounting seven sensor nodes (attached on two upper-arms, two thighs, two ankles and one in the waist area) as

shown in Figure 1. Experiments were carried out for collecting the accelerometer measurements from the piezoelectric in MTS510 card. Then the energy harvesting model illustrated in Section 4 is used to compute the amount of energy harvested at each node illustrated in Figure 1. The following values are used in the piezoelectric harvesting energy model [23], [24], with damper mass M of $7g$, force factor α of 0.00047 N/V, damper factor D of 0.0419 $Nm^{-1}s^{-1}$, sampling frequency ω of 20π rad/s, circuit resistor R of 100 $K\Omega$ and circuit capacitance C of 1.6×10^{-7} . Δt of 0.1 sec. and $U = 10$ as the window size of the acceleration moving average computation.

A human subject, as illustrated in Section 3, fitted with seven sensors, was asked to follow a pre-determined sequence of

postures (SIT, SIT-RECLINING, LYING-DOWN, STAND, WALK and RUN), each lasting for 20 sec. The plots in Figure 3 illustrate the harvested energy process for four sensors of waist, arm, thigh and ankle. Figures 3:a for all sensors show the accelerometer readings in x and y axes, as discussed in Section 3, and the corresponding, acceleration values are shown in Figures 3:b for all sensors, where Eqn. 6 is used. Next, the velocity generated at the piezoelectric in x and y directions is computed in Figures 3:c for all sensors according to procedure illustrated in Section 4 and Eqn. 7. Then, the corresponding overall displacement results ds is illustrated in Figures 3:d for all sensors by using Eqns. 5 and 8. Finally, Figures 3:e for all sensors show the harvesting energy results by plug the instant ds displacement of the piezoelectric in Eqn.4.

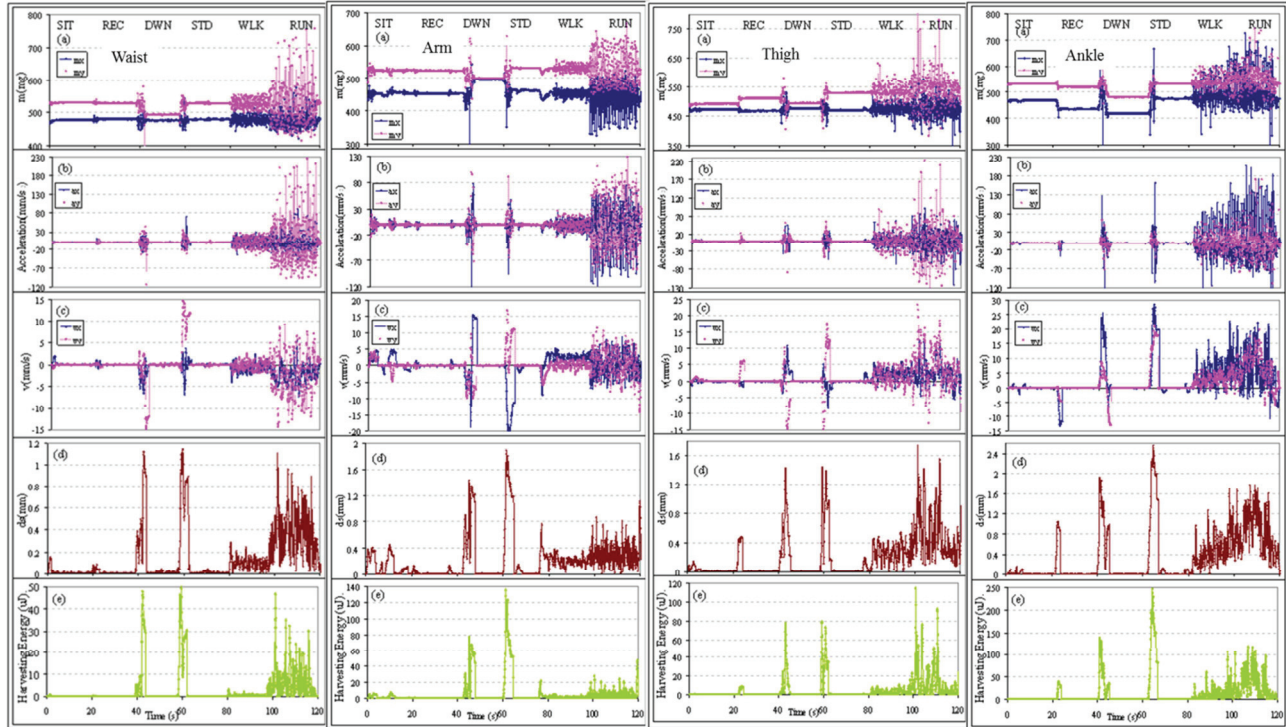


Figure 3: Waist, Arm, Thigh and Ankle sensors harvesting energy process

The following observations can be made from the plots in Figure 3. First, the harvested energy depends on the activity level of the human subject posture. As shown in the figure, while the human subject is in static postures, (i.e. SIT, SIT-RECLINING, LYING-DOWN and STAND), the amount of harvested energy is almost zero in all sensors, but when the human subject is in a high activity posture like WALK and RUN, the harvested energy is high, and it is highest in the RUN posture. The second observation is that, even during the transitions between postures where there is minimal activity, the sensors are able to harvest certain amount of energy by using the proposed model. As shown in Figure 3, when the subject moves from and to the LYING-DOWN posture there is certain amount of harvested energy around times 60s and 80s.

Another experiment was carried out for 1200 sec. as in Figure 3 by repeating the posture sequence 10 times. Figure 4 illustrates the cumulative harvested energy for the sensors places in the Waist, Arm, Thigh and Ankle. The following observations can be made from this figure. First, different sensors harvest different amount of energy depending on the sensor placement and the level of activity.

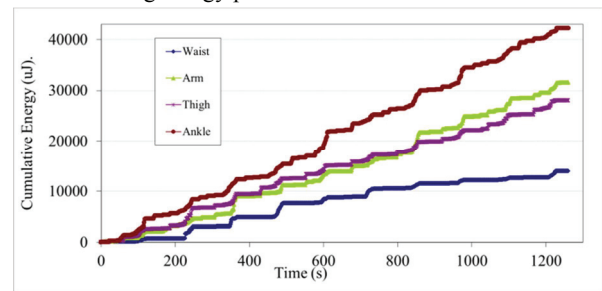


Figure 4: Cumulative harvesting energy among different sensor placements

Second, the Ankle sensor harvests the highest amount of energy, while the waist sensor harvests the lowest amount of energy, because the Ankle sensor has more flexibility to move than the other sensors. Also the level of activity is extremely high for the ankle sensor. Finally, all the harvested energy occurs during either the high activity postures or during the transitions between the postures that is at times, 20s, 40, 60, 80 sec. etc., but different amount depending on the sensor placement.

6. SUMMARY AND ONGOING WORK

Energy for the implanted, or even wearable, BSN sensors is likely to come from harvested energy sources such as piezoelectric, magnetic, and thermo-electric generators. In this paper we explore the on-body issues with sensors being powered using energy from harvested energy sources which are getting a lot of attention in the research community. In this paper we present an experimental framework for a wearable sensor network used for energy harvesting sensor. A piezoelectric generator model that harvests mechanical vibrations energy available on the wearable sensor has been developed. Performance of the proposed model was evaluated experimentally.

It was shown that the amount of harvested energy depends on the posture or the level of physical activity of the body movement and the sensor placement, which should be considered in packet routing. It was shown that the Ankle sensor harvests the highest amount of energy because the Ankle sensor has more flexibility to move than the other sensors. Ongoing work on this topic includes: 1) development of a real-time and on-body energy harvesting sensor 2) integrating energy harvesting mechanism with on-body packet routing 3) development a Kalman Filter based body movement prediction model for predictive on-body harvested energy.

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