A Quantitative Investigation of Inertial Power Harvesting for Human-powered Devices

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Introduction

- **“Power remains a key to unlocking the potential for a sustainable ubicomp reality”**
  - **Power harvesting from natural/renewable sources is a longstanding research area**
  - **Little research into capturing energy from daily human activity**
  - **Prior research done in laboratory settings**
- **Possibility of powering consumer electronics or self-sustaining body sensor networks**

Introduction

- **"First, all-day, continuous all-activity study of inertial power harvester performance using eight untethered human subjects"**
- **Untethered, wearable apparatus**
  - **6 3-axis Accelerometers**
  - **80 Hz Sampling Rate**
  - **Datasets spanning 24 hours continuous collection periods**

Introduction

- **First-principles numerical model**
  - **Developed with MATLAB Simulink**
  - **Velocity Damped Resonant Generator**
  - **Estimate available power to devices based on the developed model**
    - **Used reasonable assumptions about the size of the generator that could fit in the devices to develop the model**

Wearable Device Power Requirements

Table 1. Required power for components in consumer mobile devices and health sensors.

Electronics	Reference	Required Power
MP3 decoder chip	[10]	58 mW
RF receiver chip	[2]	24 mW
GPS receiver chip	[9]	15 mW
6D motion sensor	[25]	14.4 mW
Cell phone (standby)	[8]	8.1 mW
PPG sensor[a]	[23]	1.473 mW
Humidity	[4]	1 mW
Pressure	[16]	0.5 mW
3D accelerometer	[1]	0.324 mW
Temperature	[3]	27 μW
Wristwatch	[7]	7 μW
Memory R/W[b]	[18]	2.17 μW
A-D conversion	[26]	1 μW
RF transmission[c]	[32]	sub μW

[a] Photoplethysmograph sensor, that measures the blood p-ressure, the heart rate, and the respiration rate.
[b] With 1 Kbit/s, 1 m distance data transmission
[c] With 1 Kbit/s, 1 m distance data transmission.

Power Harvester Model

- **Inertial Generator model**
  - **Works by the body's acceleration imparting forces on a *proof mass***
- **Three Categories of Inertial Generators**
  - **Velocity-Damped Resonant Generator (VDRG)**
  - **Coulomb-Damped Resonant Generator (CDRG)**
  - **Coulomb-Force Parametric Generator (CFPG)**
- **Generator used is VDRG**

Power Harvester Model

- **Vibration-driven generators represented as a damped mass-spring system**

$$m\ddot{z}(t) = -Kz(t) - D\dot{z}(t) - m\ddot{y}(t)$$

- ***m*** **is the value of the proof mass**
- ***K*** **is the spring constant**
- ***D*** **is the damping coefficient**
- ***y(t)*** **is the displacement of the generator**
- ***z(t)*** **is the relative displacement between the proof mass and the generator**
- ***t*** **is time**

Power Harvester Model

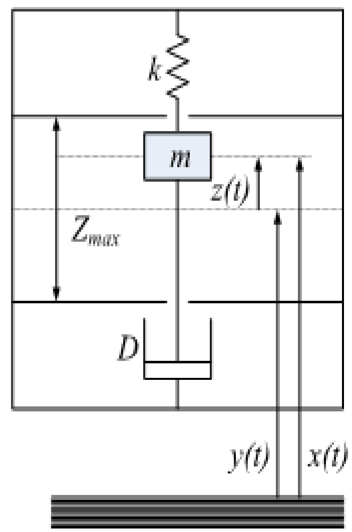


Figure 1. A generic model for the velocity-damped resonant generator.

- **In this damped mass-spring system, the electrical energy generated is represented as the energy dissipated in the mechanical damper**

Power Harvester Model

- **Important Parameters during Simulation Analysis**
  - **Proof mass *m***
  - **Spring constant *K***
  - **Damping coefficient *D***
  - **Internal travel limit Z_{max}**
- **m and Z_{max} are limited by the size and mass of the object that holds the generator**

Experimental Setup

- **Wearable Data Collection Unit**
  - **Two Logomatic Serial SD data loggers**
    - **Sampling Rate of 80 Hz**
    - **Record each input as a time series file**
  - **Six 3-axis Accelerometers**
    - **Accelerometers packaged in small container sealed against dust or sweat**
  - **Contained in Small waist-pack**
- **Allows for 24 hours of continuous operation**

Experimental Setup

- Eight Participants
  - Four Men
  - Four Women
- Wore Data Collection Unit for Three Days
  - Two weekdays
  - One weekend day
  - Acceleration was continuously monitored during these three days
- Subjects recorded their activities and time on diary sheets

Experimental Setup

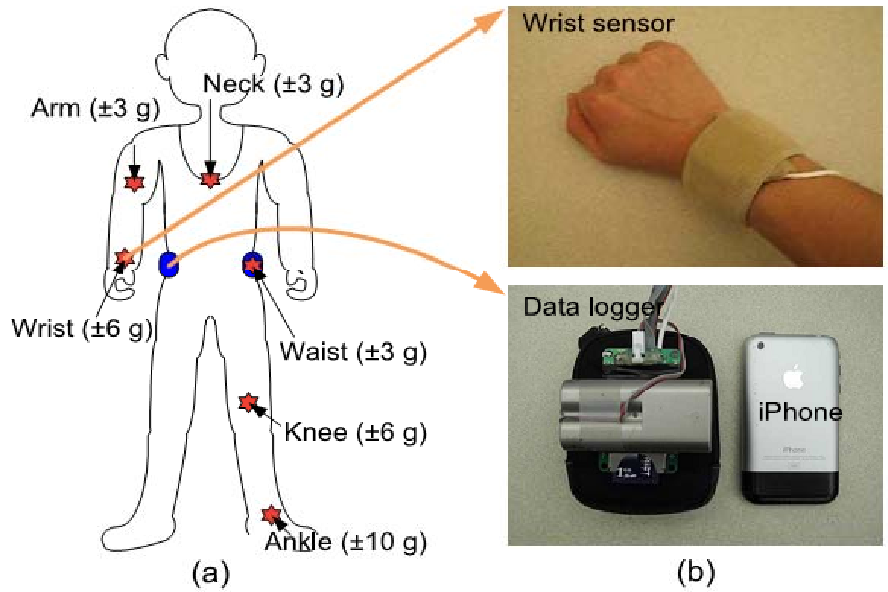


Figure 2. Figure (a) illustrates our experimental setup of six three-axis accelerometer modules and two data loggers mounted on body locations. Each accelerometer module was carefully chosen to match the probable range of acceleration in the corresponding body location. Figure (b) shows an accelerometer module mounted on the wrist and a data logger unit.

Processing of Acceleration Signals

- **High-pass filtered measured acceleration signals**
  - **0.05 Hz cutoff frequency**
- **Obtain displacement of the accelerometer through double-integrating the acceleration dataset**
- **Feed the resulting displacement time series into the VDRG model**

Spectra of the Acceleration Signals

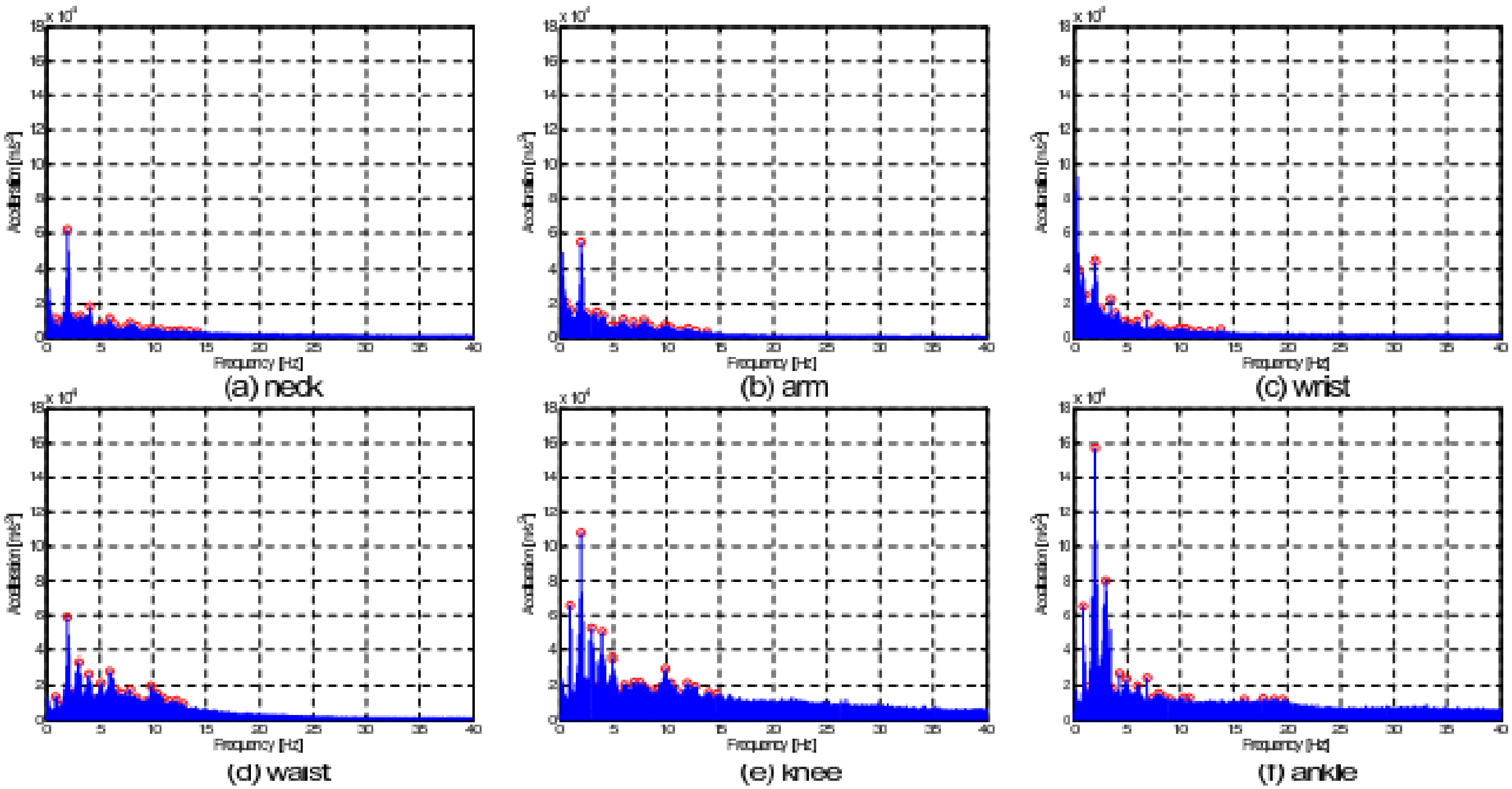


Figure 4. The spectra of the acceleration signals from six locations.

Simulation Setup

- **Three simulated devices**
  - **Wristwatch**
    - **2g / 4.2cm**
  - **Cell phone**
    - **36g / 10cm**
  - **Shoe**
    - **100g / 20cm**

Table 2. Power harvester configuration used for simulation.

	Wristwatch	Cell Phone	Shoe
Neck	○	○	
Arm		○	
Wrist	○		
Waist		○	
Knee			
Ankle			○

Power Estimation Procedure

- **Acceleration data split into 10 sec fragments**

$$E_d = \int_{Z_1}^{Z_2} F \cdot dz$$

$$E_d = \int_{Z_1}^{Z_2} D\dot{z} \cdot dz = \int_{t=0}^{T} D\frac{dz}{dt} \cdot \frac{dz}{dt} dt = D\int_{t=0}^{T} (\dot{z})^2 dt.$$

$$P_{average} = \frac{1}{T}E_d = \frac{D}{T}\int_{t=0}^{T} (\dot{z})^2 dt.$$

Where z is the average displacement and T is the time

Power Estimation Procedure

- **Assume a VDRG would use a single axis**
- **Find preferred orientation of VDRG based on which axis provides the most power**
- **Search for optimal D which maximizes P**
  - **All other variables determined previously**
- **After D is chosen the generated electrical power can be estimated**

Power Estimation Result

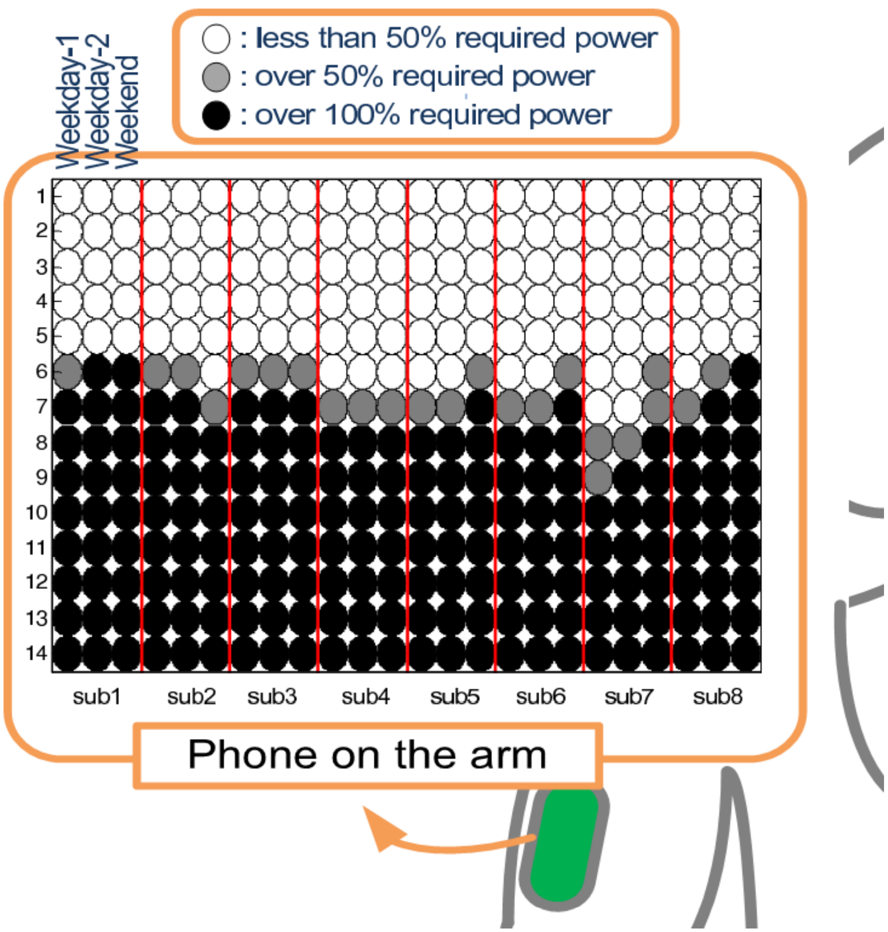
Table 3. Generated output power: C1-a watch hanging on the neck, C2-a watch on the wrist, C3-a phone hanging on the neck , C4-a phone on the arm, C5-a phone on the waist, and C6-a shoe on ankle

Sub	C1 (μW)	C2 (μW)	C3 (mW)	C4 (mW)	C5 (mW)	C6 (mW)
	14	164	0.2	1.1	0.1	2.8
1	31	265	0.6	1.8	0.1	4.2
	25	195	0.7	1.7	1.4	12.6
	48	167	0.3	1.4	0.1	2.8
2	35	162	0.4	1.4	0.2	2.9
	10	67	0.1	0.7	0.2	2.6
	16	127	0.4	1.2	0.5	6.0
3	26	137	0.2	1.3	0.2	2.3
	16	153	0.2	1.3	0.4	3.4
	8	57	0.3	0.5	0.3	2.6
4	13	66	0.4	0.7	0.3	3.1
	12	84	0.5	0.7	0.4	4.0
	20	141	0.7	0.6	0.6	10.5
5	19	143	0.7	0.6	0.6	11.5
	36	170	1.2	1.1	1.4	12.0
	37	130	0.7	0.6	0.1	1.0
6	37	143	0.7	0.7	0.2	10.4
	73	225	1.4	1.3	0.6	3.1
	10	54	0.1	0.3	0.1	3.1
7	18	96	0.7	0.5	0.7	4.1
	30	322	0.3	0.9	0.3	0.7
	32	144	0.2	0.7	0.5	3.7
8	29	176	0.2	1.2	0.3	1.8
	99	346	1.7	2.1	0.8	6.5

Power Estimation Result

- Typical Efficiency for Mechanical to Electrical Conversion is 20%
- Energy Generated is storable
- Average Electrical Power Expected
  - Wristwatch
    - 155 ± 106 µW
  - Cellphone
    - 101 ± 0.46 mW
  - Shoe
    - 4.9 ± 3.63 mW

Power Estimation Result



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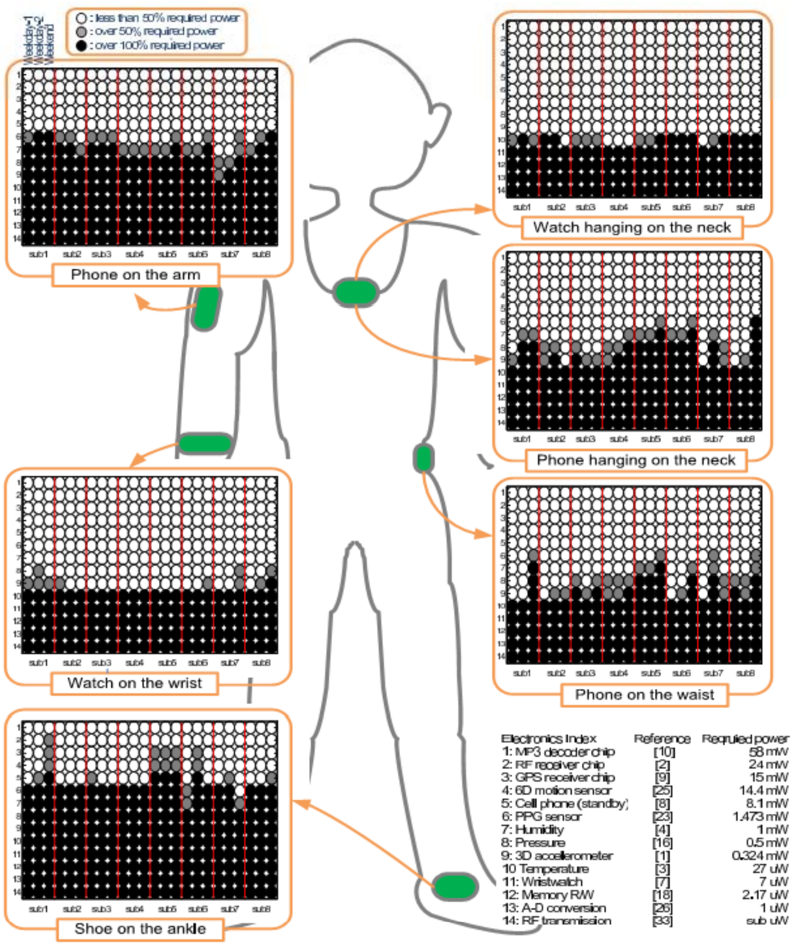
Power Estimation Result



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Results

- **Output power is insufficient to continuously run the higher demanding electronics**
  - **Can be used to charge a battery for intermittent operation**
  - **Possibly charge a backup battery for when standard recharging options not available**
- **Low-power electronics can be powered continuously**

Results

- **From the diary sheets of participants it is possible to find the generated power from certain activities**

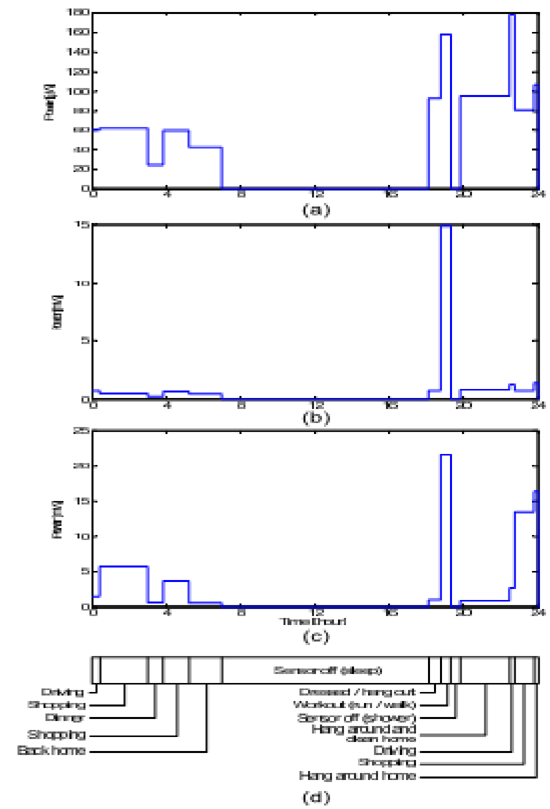

Figure 7. Power generated with a watch on the wrist, a phone on the arm, and a shoe on the ankle Friday through Saturday afternoon for the subject 1. (a) watch on wrist, (b) phone on arm, (c) shoe on ankle, (d) activity annotation.

WPI

Future Work

- **Possible to increase power output with heavier proof mass**
  - **Balanced with increased strain from additional weight**
- **Use all three axis to generate power**
  - **Harvester with three mass-spring systems**
- **Generalize the K/D measurements across subjects**
- **Adaptive Tuning of VDRG**

Conclusion

- First 24-hour Continuous study of inertial power harverster performance
- Analysis of the energy that can be garnered from 6 locations on the body
- Shown feasibility to continuously operate motion-powered wireless health sensors
- Motion-generated power can intermittenly power devices such as MP3 players or cell phones

Questions?