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WIRELESS MONITORING FOR AMBIENT VIBRATIONS: INVESTIGATE POTENTIAL AMBIENT VIBRATION SOURCE FOR ENERGY HARVESTING

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ABSTRACT

WIRELESS MONITORING FOR AMBIENT VIBRATIONS: INVESTIGATE POTENTIAL AMBIENT VIBRATION SOURCE FOR ENERGY HARVESTING

(*Keywords: Energy Harvesting, Vibration, Piezoelectric*)

Ambient vibration is one of the main sources of energy harvesting and for the past few years it has attracted many interests in design and development of vibration based micro generators. Energy harvesting is also known as energy scavenging is the process of extracting residual ambient sources into usable electric energy which can be used to power-up small electrical devices that require very low power consumption such as wireless sensor nodes and wearable devices. The aim of this project is to investigate useful ambient vibration sources that have a great potential for energy harvesting. The research work comprises process of identifying, measuring and analyzing the identified ambient vibrations which is in the scope of low level of acceleration; <1g. Then, the obtained vibration raw data will be transformed from the time domain into frequency domain by using appropriate mathematical tool. At the end of the project, a summary of various vibration sources is presented in terms of vibration frequency and acceleration level. Suggestions of micro generators developed by other researchers that suit to the identified useful ambient vibration sources for energy harvesting applications is also presented.

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List of Abbreviations

CNC	Computer Numerical Control
FFT	Fast Fourier Transform
SDOF	Single Degree of Freedom

List of Symbols

ε	-	Dielectric constant of the piezoelectric material
η	-	Net displacement of accelerometer
φ	-	Phase
ω	-	Object excited angular frequency
ω_n	-	Undamped natural frequency
ω_r	-	Fundamental resonant frequency
ζ	-	Damping ratio
ζ_e		Electrical damping ratio
ζ_m		Mechanical damping ratio
ζ_T	-	Total damping ratio
a_{in}	-	Input acceleration
B	-	constant related to the distance from the Piezoelectric layer to the neutral axis of the structure
b_e	-	Induced damping for electrical
b_m	-	Induced damping for mechanical
C_p	-	Capacitance of the piezoelectric
c_v	-	Damping coefficient
d_{31}	-	Piezoelectric charge constant
E_T	-	Elastic constant for the composite structure
e_T	-	Mechanical stiffness
H	-	Amplitude
h_p	-	Piezoelectric material thickness
i	-	Current
j	-	Imaginary number
k	-	Spring constant
k_{31}	-	Piezoelectric coupling factor

M	-	Lump mass
m	-	Accelerometer system lump mass
n	-	Transformer turn ratio
P	-	Power
P_{max}	-	Maximum power
R	-	External resistive load
V	-	Voltage
Y	-	Amplitude of vibration
$y(t)$	-	Displacement relative to the system housing
$z(t)$	-	Net displacement

Chapter 1 Introduction

1.1 Introduction

Over the past few years with the advancement of MEMS (Micro-Electro-Mechanical Systems) technology, portable and wireless electronic devices have shown a great increasing range of applications with reductions in cost and size, and increases in functional capability (Mitcheson, P.D., *et al.* 2008; Bouendeu, E., *et al*., 2011).

The dependence of these devices on external power supplies and batteries are minimized by using micro generators that generate energy from ambient sources such as thermal gradient, light, radio frequency (RF) and vibration (Mitcheson, P.D., *et al.* 2008 ; Kok, S.L., *et al.* 2010). Among these sources, vibration is particularly important due to its abundance and has attracted many interests from researchers and companies in designing vibration based micro generators (Zorlu, O., *et al.*, 2011).

Although there are lots of research works being presented with respect to the vibration based micro generators, however there is insufficient of data pertaining to the vibration frequency and acceleration being investigated and presented in the literature. This data is useful to the researchers who are designing ambient vibration based micro generators and has been a driven force to carry out investigation on useful ambient vibration source for energy harvesting.

In this research, ambient vibrations generated from the household electrical appliances, vehicles and machineries that are useful for energy harvesting will be identified and investigated. The investigation results which comprise ambient vibrations frequency and acceleration are summarized and presented in detail in chapter four.

1.2 Project Objectives

The main aim of this project is to identify on useful ambient vibrations that have a great potential for energy harvesting. In order to achieve the targeted aim, a few objectives as follows have been identified.

1. To investigate on useful ambient vibration source that is within one gravity (1 g = 9.81 m/s^2) of acceleration. These ambient vibration sources are generated from the vehicles, electrical appliances and machineries.
2. To study and analyze the data in the form of FFT (Fast Fourier Transform) by using appropriate mathematical tool.
3. To summarize and match the identified useful ambient sources with appropriate micro generators developed by other researchers from the literature.

1.3 Problem Statement

Over the last few years, there are a lot of publications and demonstrations have been published and carried out by researchers, academicians and companies over the world in the field of vibration based energy harvesting (Khaligh, A., *et al*., 2010).

However there is insufficient of information that can be obtained from the literature pertaining to the ambient vibration frequency and acceleration in g-level which are very important in determining the right micro generators for the right ambient vibration sources.

Resonance occurs when a system oscillates with larger amplitude than others at a certain frequencies called resonant frequency. Micro generators have their own natural frequency. In literature, resonant frequency is referred to as input frequency when the natural frequency of the micro generators are matched with frequency of the vibration sources where they are mounted on and hence optimum electrical power is generated. Explanation on this relation will be discussed in chapter two.

Table 1.1, Table 1.2 and Table 1.3 summarize some of the micro generators that are published in the literature related to electromagnetic, electrostatic and piezoelectric micro generators.

Table 1.1: Published electromagnetic micro generators

Author	Year	Generator Volume [cm³]	Proof Mass [g]	Input Frequency [Hz]	Power (un-processed) [μW]	Power (processed) [μW]	Power Density [μW/cm³]
Li	2000	1	0.22	60	-	100	100
Li	2000	1	0.22	120	-	100	100
Ching	2000	1	-	107	1.5	-	1.5
Ching	2000	1	-	104	5	-	5
Li	2000	1.24	210	64	-	10	8.06
Ching	2001	1	200	60	-	680	680
Ching	2001	1	200	110	-	680	680
Ching	2002	1	200	60	-	830	830
Ching	2002	1	200	110	-	830	830
Lee	2003	7.3	0.14	85	830	-	114
Saha	2006	-	43	13.1	2000	-	-
Saha	2006	-	25	84	3200	-	-
Huang	2007	0.04	0.03	100	1.44	-	40
Perpetuum	2008	131	-	99	-	800	6.1
Perpetuum	2008	131	-	99	-	3500	27
Perpetuum	2008	131	-	99	-	40000	306
Ferro Solutions	2008	133	-	60	800	-	6
Ferro Solutions	2008	133	-	60	3100	-	23
Ferro Solutions	2008	133	-	60	10800	-	81
Ozge Zorlu	2011	2.96	-	10	544.7	-	184

Table 1.2: Published electrostatic micro generators

Author	Year	Generator Volume [cm³]	Proof Mass [g]	Input Frequency [Hz]	Power (un-processed) [µW]	Power (processed) [µW]	Power Density [µW/cm³]
Tashiro	2000	-	640	4.76	-	58	-
Tashiro	2002	15	780	6	36	-	2.42
Miyazaki	2003	-	5	45	-	0.21	-
Arakawa	2004	0.4	0.65	10	6	-	15
Despesse	2005	18	104	50	1760	1000	56
Tsutsumino	2006	-	-	20	278	-	-
Tsutsumino	2006	-	-	20	6.4	-	-
Mitcheson	2006	0.6	0.12	20	2.4	-	4

Table 1.3: Published piezoelectric micro generators

Author	Year	Generator Volume [cm³]	Proof Mass [g]	Input Frequency [Hz]	Power (un-processed) [µW]	Power (processed) [µW]	Power Density [µW/cm³]
Glynne-Johnes	2000	0.53	-	80	1.5	-	2.83
Roundy	2003	1	8.5	120	80	-	80
Roundy	2003	1	7.5	85	207	90	90
Roundy	2003	1	8.2	60	365	180	180
Wright	2005	4.8	52.2	40	1700	700	145
Lefeuvre	2006	113	228	56	-	10000	88
Lefeuvre	2006	113	228	56	-	300000	2650
Tanaka	2005	9	-	50	180	-	20
Duggirala	2006	-	-	38	0.17	-	-
Duggirala	2006	-	-	38	1.13	-	-
Ng	2005	0.2	0.96	100	35.5	16.3	82
Ferrari	2006		82	41	-	0.27	-
Mide	2008	40.5	-	50	-	8000	198
Mide	2008	40.5	-	150	-	1800	45

1.4 Project Significance

Upon completion of this research, a summary of identified ambient vibration sources will be presented. Important ambient vibration characteristic such as their vibration frequency and acceleration in g-level will be tabulated. These data can be a very good source of reference to other researchers and companies who are keen to design and develop vibration based micro generators.

1.5 Scope of works

The scope of the research work is described by using the K-chart and is depicted in Figure 1.1. The highlighted texts refer to the scope and the flow of the project. The project is classified under wireless sensor network field of study, narrowed down to the sensor nodes power sources, energy harvesting, motion or kinetic, ambient vibration, investigation of sources until it reaches down to the study of low level of acceleration that is within one gravity.

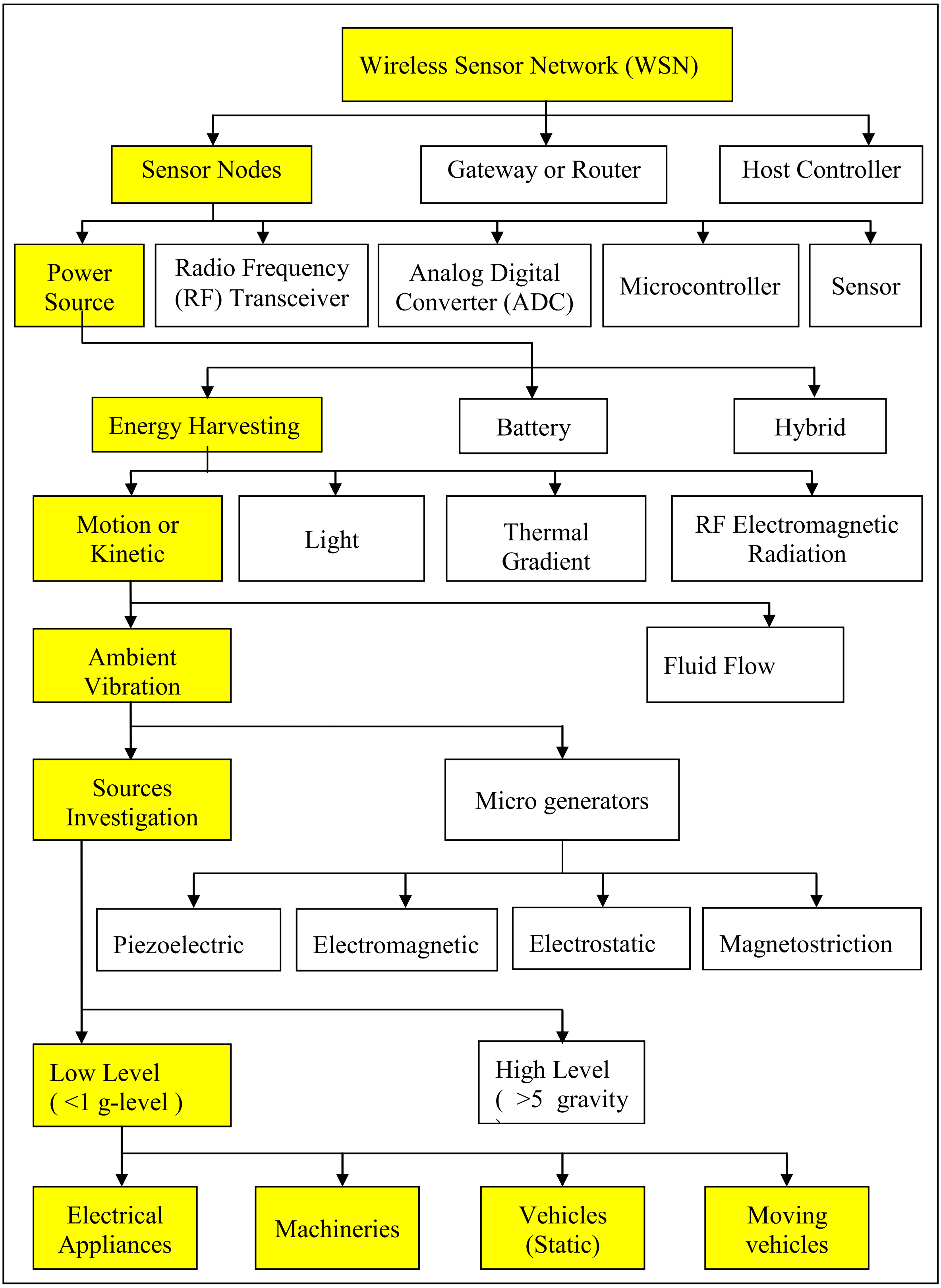

Figure 1.1: Project K-chart

Chapter 2 Literature Review

2.1 Introduction

The background of wireless sensor network will be presented in this chapter and discussing on the potential energy sources harvested from the ambient environment for powering low-power electronic devices.

In order to investigate the potential ambient environment energy harvesting sources, the mechanism of a few energy harvester or also known as micro-power generators, will be discussed, these include electromagnetic (Zorlu, O., *et al.*, 2011; Amirtharaja, R. And Chandrakasan, A.P., 1998), electrostatic (Meninger, S., 2001) and piezoelectric (Kok, S.L., *et al.*, 2010; Roundy, S. and Wright, P.K., 2004). It is important to know the characteristics of the sources such as the level of acceleration and excitation frequency which are important for designing appropriate energy harvester suit to different energy sources that are available in the surrounding of the energy harvesters.

Since vibration is ubiquitous and available everywhere especially those generated by engines or machines that are in operation. The function of the devices that are being used to measure the ambient environment vibration sources; G-Link and ADXL 321 accelerometer, will be explained in this chapter.

2.2 Wireless sensor network

Wireless sensor network consists of base station that can communicate with each other via radio link. Data is collected at wireless sensor node and transmitted to base station directly or uses other wireless sensor node to forward data to base station (Wilson, J.S., 2005).

The ideal wireless sensor which are networked have a low power consumption, low cost of implementation, smart and software programmable, fast data acquisition and accurate and requiring little intervention by human being in maintaining the devices.

There are a few advantages of wireless sensor network compared to wired sensor. Wired sensors have bundles of lead and fibre optic wire which tend to be broken and connection failure. These impose high installation and long term maintenance cost. Wireless sensor network eliminates these costs and also easy to be installed by eliminating wires and connectors. Wireless sensors which are usually installed remotely and embedded in building require less maintenance and sometime not assessable to be maintained, therefore the electrical power source using battery is the major concern (Wilson, J.S., 2005; Priya, S. and Inman J.D., 2009).

There are few methods to increase the lifetime of sensor nodes. One of which is through power generation, power conservation and power management. Power generation uses environmental sources such as solar, vibration and thermal. Power conservation uses TDMA (time division multiple access) where a node can power down or sleep between its assigned time slots and waking up in time to receive and transmit messages. Power management uses software power management techniques to decrease the power consume by RF sensor node (Lewis, F.L, 2004; Arms, S.W. *et al*., 2005).

2.3 Energy harvesting sources

This section aims to provide an overview of energy harvesting sources which are solar, air flow, and vibration. The advantage and disadvantage of energy harvesting sources are also discussed.

Solar energy has been used by inhabitants of earth planet since the beginning of their existence. In direct sunlight at midday, the power density of solar radiation on the earth surface is roughly $100mW/cm^3$ (Roundy, S., *et al.*, 2004). The advantages and disadvantages of solar energy harvesting is shown in Table 2.1.

Table 2.1: Advantages and disadvantages of solar energy

Advantages	Disadvantages
1) Mature / well established	1) Limitation on placement
2) Abundant energy sources	2) Must be free from obstruction
3) Inexpensive	3) Energy delivered for only part of the day
4) Highly compatible with electronics (provide voltage and current level that can be matched with microelectronics)	4) If aiming for small scale harvesters, it is difficult because power output directly linked to surface area.

Air flow is another potential ambient environment energy harvesting sources. In the atmosphere or wind exist as a result of pressure differences causes by the sun heating up different parts of the atmosphere. Approximately 2% of the sun's energy reaching the earth is converted into wind energy (Chen, C.T., *et al*., 2006). Human have used wind as a power source for thousands of years for propelling ships and boats by use of a sail and for milling grain through the use of windmills. The air flow harvesting sources is converted into electrical energy using the large scale wind turbine. Then, a transmission system exists which comprises a hub, main shaft plus bearing, gearbox and three phases AC generator that can be connected to the three phase main supply. The advantage of large scale wind turbine is it can achieve efficiencies of 50% or more. The disadvantages of wind turbine are it has many moving parts and complicated construction. In addition, it cannot easily be miniaturised due to complicated construction.

Vibration energy represents the most abundant source next to solar. Vibration can be found in a wide variety of natural, industrial, commercial and transport environments such as vehicle engine compartments, trains, speakers, household appliances, machinery and human. In terms of vibration energy, there are three methods of converting into electrical energy which are using piezoelectric, electromagnetic, electrostatic, and magnetorestrictive. The advantage of vibration is that it is abundant and present in almost everywhere as long as there is mechanical activity. However, one of the disadvantages of vibration source is uncertainty, where the amplitude and frequency of the source is varied all the time. Besides, this source can be intermittent with periods of no vibration. In addition, most vibration harvesting devices are resonant structures and ambient environmental vibration tends to have higher acceleration values at lower frequencies. The smaller the device, the more difficult it is to achieve high acceleration value, therefore generating low electrical output power.

There are many other ambient environment energy sources that can be harvested and converted into useful electrical power, however, vibration source is the most prominent and easy to be harvested by small energy harvester such as piezoelectric and electromagnetic generators. Therefore, vibration source will be the focus in this project.

2.4 Overview of Micro generators

Vibration based micro generators can be classified into three most common type; electromagnetic, electrostatic and piezoelectric. Figure 2.1 depicts these three types of micro generators outlook. Some of these micro generators which published in the literature will be matched with the identified potential ambient vibration sources that are useful for the application of energy harvesting. The general techniques used with respect to these types of micro generators are explained as follows.

2.4.1 Piezoelectric micro generator working principle

Strain or deformation of a piezoelectric material causes charge separation across the device, producing an electric field and consequently a voltage drop proportional to the stress applied. The oscillating system is typically a cantilever beam structure with a mass at the unattached end of the lever, which provides higher strain for a given input force (Roundy S. and Wright, P.K., 2004).

2.4.2 Electrostatic micro generator working principle

Electrostatic micro generator depends on the variable capacitance of vibration-dependent varactors (Meninger, S., *et al*., 2001). A varactor, or variable capacitor, which is initially charged, will separate its plates by vibrations; in this way, the change in capacitance causes either voltage or charge increase.

2.4.3 Electromagnetic micro generator working principle

This technique uses a magnetic field to convert mechanical energy to electrical energy (Amirtharajah, R. and Chandrakasan, A.P., 1998). A coil attached to the oscillating mass is made to pass through a magnetic field, which is established by a stationary magnet, to produce electric energy. The coil travels through a varying amount of magnetic flux, inducing a voltage according to Faraday's law.

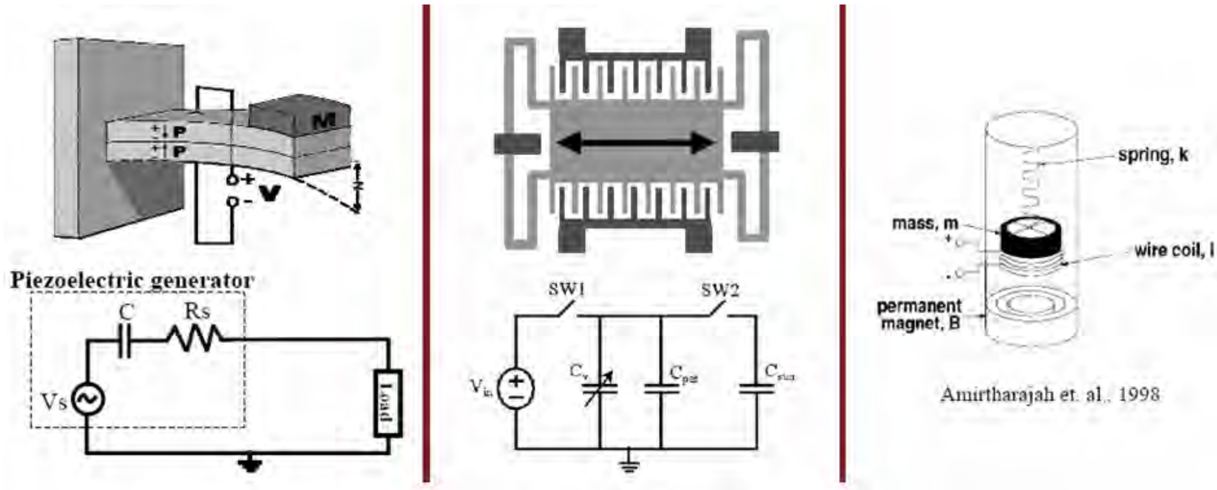

Figure 2.1 Vibration based energy harvesting micro generators (Roundy, S. and Wright, P.K., 2004; Meninger, S., *et al.*, 2001; Amirtharajah, R. and Chandrakasan, A.P., 1998)