HYBRID ENERGY HARVESTER USING OPTIMISED PIEZOELECTRIC AND SOLAR POWER FOR SELF-POWERED GLOBAL POSITIONING TRACKING SYSTEM

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DEDICATION

This thesis is dedicated to my father (Mohamad Ismail bin Ja'apar), who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother (Rohani binti Ibrahim), who taught me that even the largest task can be accomplished if it is done one step at a time.

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ABSTRACT

The rapid advancement of Wireless Sensor Nodes (WSNs) in conjunction with the Global Positioning System (GPS) tracker has resulted in various applications, including health monitoring, industrial process monitoring, and security system monitoring. However, a significant problem of the GPS device is short tracking and positioning due to high power consumption. This study develops a Self-Power Global Positioning System (SP-GPS) for tracking objects powered by hybrid energy harvesting sources, piezoelectric and solar. First, the Taguchi Design of Experiment (DOE) method is used to optimise the design of the piezoelectric energy harvester based on ruler and cylinder designs. Then, the piezoelectric is combined with solar to create the hybrid Power Management Unit (PMU) for the sustainability of the SP-GPS Tracker device. Finally, to develop the SP-GPS tracking system, the SP-GPS tracker is integrated with SP-GPS Base Station. The results demonstrated that the optimum design for a ruler-based piezoelectric generator is five centimetres and a mass of two grams. Meanwhile, the optimum design for a cylindrical shape of piezoelectric is the glass ball-bearing material with a mass of five grams, and the height between the ball-bearing and casing surfaces is five millimetres. Based on the field experiments around the Universiti Teknologi Malaysia campus by motorcycle and a car with a distance of 1.74 km and average speed from 11.8 to 24.1 kmh, the total energy generated by hybrid energy harvester of piezoelectric design is a cylinder (glass), 6.07 kWh and ruler, 2.85 kWh, respectively. On the other hand, the piezoelectric cylinder design achieved higher total energy of 6.26 kWh and 2.96 kWh. The reason is that the latter design can induce considerable vibration with the impact of the heavy mass glass ball-bearing on the cylinder surface. The estimated life span of SP-GPS Tracker is computed and found can be up to approximately two years and three months for a motorcycle and one year and five months for a car. Therefore, the current study benefits long-term tracking and monitoring, such as wild animals or vehicles, in observing their pattern movement.

ABSTRAK

Kemajuan Nod Pengesan Tanpa Wayar (WSN) yang pesat bersama dengan Sistem Kedudukan Global (GPS) telah menghasilkan pelbagai aplikasi, termasuk pemantauan kesihatan, pemantauan proses industri, dan pemantauan sistem keselamatan. Walau bagaimanapun, masalah utama pada peranti GPS adalah penjejakan yang pendek dan kedudukan kerana penggunaan kuasa yang tinggi. Kajian ini adalah untuk membangunkan Sistem Kedudukan Global Kuasa Kendiri (SP-GPS) untuk mengesan objek yang dijanakan oleh sumber tenaga hibrid dari piezoelektrik dan solar. Pertama, kaedah reka bentuk Eksperimen Taguchi (DOE) digunakan untuk mengoptimumkan reka bentuk penuai tenaga piezoelektrik berdasarkan reka bentuk pembaris dan silinder. Kemudian, piezoelektrik digabungkan dengan solar untuk mewujudkan Unit Pengurusan Kuasa hibrid (PMU) bagi kelestarian peranti pengesan SP-GPS. Akhirnya, untuk membangunkan sistem penjejakan SP-GPS, penjejak SP-GPS disepadukan dengan Stesen Pangkalan SP-GPS. Hasil kajian menunjukkan bahawa reka bentuk optimum dari penjana piezoelektrik berasaskan pembaris adalah lima sentimeter dan jisim dua gram. Manakala, reka bentuk optimum bagi piezoelektrik berbentuk silinder memerlukan bahan bebola kaca dengan jisim lima gram, dan tinggi diantara permukaan bebola dan permukaan sarung adalah lima milimeter. Berdasarkan eksperimen lapangan di sekitar kampus Universiti Teknologi Malaysia menggunakan motosikal dan kereta dengan jarak 1.74 km dan kelajuan purata dari 11.8 kmj ke 24.1 kmj, jumlah tenaga yang dihasilkan dari tenaga hibrid piezoelektrik dengan reka bentuk silinder (kaca) masing-masing ialah 6.07 kWj dan pembaris, 2.85 kWj. Sebaliknya, reka bentuk piezoelektrik silinder mencapai jumlah tenaga yang lebih tinggi iaitu 6.26 kWj dan 2.96 kWj menggunakan kaca dan bebola besi Ini disebabkan oleh reka bentuk besi dapat menghasilkan getaran yang cukup dengan kesan jisim bebola kaca yang berat pada permukaan silinder. Jangka hayat pengesan SP-GPS telah dihitung dan didapati anggaran jangka hayatnya ialah dua tahun dan tiga bulan untuk motosikal dan satu tahun dan lima bulan untuk kereta. Oleh itu, kajian semasa memberi manfaat pengesanan jangka panjang dan pemantauan, seperti pemantauan haiwan liar atau kenderaan, dalam memerhati pergerakan coraknya.

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LIST OF ABBREVIATIONS

AC	-	Alternate Current
AOA	-	Angle of Arrival
DC	-	Direct Current
EHs	-	Energy Harvesting
EH-WSNs	-	Energy Harvesting for Wireless Sensor Nodes
GPS	-	Global Positioning System
I	-	Current
IC	-	Integrated Circuit
LOS	-	Line of sight
LSA	-	Lazy Scheduling Protocol
MCU	-	Micro-Controller Unit
MPPT	-	Maximum Power Point Tracking
P	-	Power
PMU	-	Power Management Unit
RF	-	Radio Frequency
RSSI	-	Received Signal Strength Indicator
RTC	-	Real-Time Clock
Rx	-	Receiver
SP-GPS Tracker	-	Self Power - Global Positioning System (GPS) Tracker
SSHI	-	Synchronised Switch Harvesting on Inductor
PZT	-	Piezoelectric Transducer
PV	-	Photovoltaic
TDOA	-	Time Different of Arrival
TEG	-	Thermal Energy Generator
TOA	-	Time of Arrival
Tx	-	Transmitter

V	-	Voltage
VEHs	-	Vibration Energy Harvesting
WSNs	-	Wireless Sensor Nodes

LIST OF SYMBOLS

σ	-	Standard deviation
π	-	3.142

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CHAPTER 1

INTRODUCTION

1.1 Introduction

In advanced microelectronics engineering over the last decade has seen a rapid development of ultra-low power Wireless Sensor Nodes (WSN) and systems [1–4]. Sensor systems has an increasing interest for a wide variety of applications, ranging from structured health monitoring to industrial process control [5–7]. The popularity of sensors in many systems are mostly because of its mobility advantages

Wireless sensor technology has a number of advantages over wired sensor technology, which includes the ability to place sensors in regions that are inaccessible to wired sensors. Without considering difficulties such as physical wiring and permitted cabling requirements, the wireless method can indeed reduce costs and time [8, 9]. Physical wiring does deter or limit the functions of sensor and due to the wireless capability, WSNs have a wide range of applications in human, environmental, agriculture and meteorological activities [10–13]. As an example, using a Bluetooth strapped to the waist, human heart rate data can be wirelessly transmitted to a treadmill [14–17]. A wireless electrocardiograph (ECG) with the same platform can be transmitted to a physician. Another example is the wireless ZigBee module-equipped smart meter that will monitor energy consumption in residential and commercial buildings and offers feedback to the user to aid in decision-making and suggestions for energy conservation [18]. In general, WSNs are inherent in structural monitoring, industrial processes, security, position tracking, and radio frequency identification (RFID) [19–22].

Nowadays, localisation using wireless sensor network is a trend in finding and estimating location of target object [23–29]. The WSN deployed usually consist of hundreds to thousands of nodes with limited computing power and limited memory, where the short battery life is the main obstacle in distance estimation of nodes even though sensors is the most likely way that is more efficient. Localisation is a very important data required in various sensor applications, where the accuracy of distance estimation should be higher while keeping cost of localisation to a minimum. The Global Positioning System (GPS) used for monitoring movement of the target sensors, is one of the localisations methods used. The GPS tracker is a very straightforward method in localisation positioning using direct Line of Sight (LOS) approach. GPS tracker are widely used as in missile guidance, positioning of individuals [25], habitat monitoring [24,30–32], medical diagnostics [7,26,33,34], and object tracking [27,35,36]. Besides the LOS approach, some combination of tracking methods was introduced successfully such as combining GPS coordinate, acceleration and direction or movement of sensors [37,38]. It is important to highlight that the use of GPS uses a significant amount of energy and needs to be conserved [39].

The energy harvesting techniques have been broadly researched as a possible alternative of energy supply technology in WSN especially in nodes tracking where the nodes are always mobile and battery replacement or power top-up [29,40–43]. It is important to imply that power consumption is the key concern in WSNs tracking applications protocol [38,44]. Tracking by using WSNs will drain the energy rapidly and cause the sensor to be out of power and will be disconnected from the network which will significantly impact the performance of the said application. Therefore, energy harvesting system is required in WSN, to extend the lifetime of sensor nodes. Energy harvesting system consists of two important processes, namely energy collection and energy storage. Energy collection is done using the energy harvesting sources available in our environment such as mechanical (vibration, pressure, etc.), thermal energy (energy from heat), radiated energy (solar, infrared RF), chemical energy and nuclear [45,46]. Each of these energy harvesting sources is characterized by different power densities. Then the harvested energy will be stored using batteries or supercapacitors. [40,41] discussed on a computer architecture built to map the habit of pink iguanas: a recently discovered population on the remote Galapagos Islands. Without contact networks, few iguanas exist in a comparatively small area (about 25 km^2 above Volcano Wolf, Isla Isabela).

The design blended ultralow sleep mode with high-powered consumption connectivity capabilities. However, the design only used a single energy harvesting technology such as solar energy, which produces a lower power because of the size of the solar panel. On the other hand, vibration energy harvesting (VEH) using piezoelectric generators is an attractive alternative energy source that can provide energy autonomy to wireless sensor devices [29,47–50]. The harvested ambient energy may be sufficient to provide additional power to the sensors. Also, with the advancement in ultra-low microelectronics and ultra-low-power wireless microcontroller units, the power consumption of sensor nodes can be greatly reduced [28, 51–55]. The WSNs will be more energy efficient, and this will further reduce the dependence on batteries. In the past few years, much work has been done to generate effectual power output by introducing improvements such as innovative design to reduce the weight and size of the harvester [28, 29, 56, 57]. The major challenge is finding a more reliable and effective way to generate more voltage output from a low-frequency range. With the advances in technology, small-scale energy harvesting and large-scale vibration energy harvesting provide promising solutions to the energy crisis.

Hybrid energy harvesting systems have been proposed to address single energy harvester insufficiency [57, 58]. Multi-energy conversion mechanism hybridisation improves space utilisation and power output. Monitoring infrastructure, industry, smart transportation, human healthcare, marine monitoring systems, and aerospace engineering are possible future Internet-of-Things (IoT) applications. This research focuses on vibrational and thermal energy harvesting technologies in hybrid energy harvesting.

1.2 Research Background

To date, researchers have demonstrated an increasing interest in tracking WSNs without GPS over the last few decades [28, 59–63]. These techniques will reduce power consumption and increase the lifetime of WSNs by utilising the fewest possible sensors [29, 34, 55–57]. However, this technique has limitations in terms of localisation accuracy and system complexity. Thus, the use of GPS receiver module has gained popularity due to its superior accuracy in location coordinates and line of sight (LOS) to the satellite. However, the fundamental issues with wireless GPS sensor node tracker are high power consumption and short-lived batteries. WSN tracking with GPS still has a chief benefit, a position efficiency for object tracking and outdoor applications. There have been several discussions on integrating WSN tracking with GPS receiver for low-power consumption [29, 34, 56, 57]. The goal in sensors is a battery that provides node control and can run reliably for several weeks or months before power depletion. Conventionally, the batteries must be changed or recharged in long-term operation or monitoring. Unfortunately, this is a problem for compliance applications, especially on whether to charge the battery regularly or within a week since it includes personal protection and classified operations [34, 55]. This discussions show clearly that using GPS will provide better localisation accuracy but will be offset by high power consumption. It is important that this problem be solved or reduced and energy harvesting seems to be a good option to prolong the sensor lifetime.

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Recently, most researchers have been developing and testing Long Range (LoRa) transceivers for localization of GPS tracking devices [55, 64, 65]. The GPS LoRa tracking system was used to track vehicle [66], human [34, 67], boat [68] and also animal [32]. An open-source tracking system has been developed to determines the location and speed in real-time. Transponders transmit location data to a cloud server via LoRa periodically via a gateway. However, the researcher developed a GPS LoRa-based tracker using an Arduino microcontroller or Raspberry Pi that connected to a LoRa Shield. This technique demonstrates the GPS tracker's high-power consumption and larger size. This discussion demonstrates unequivocally that while a GPS tracker LoRa-based system consumes little power, it will affect the tracker's size. It is critical that this issue is resolved or that the GPS tracker's size is reduced to allow for additional applications, such as human or animal tracking.

The energy harvesting serves as a replacement for the energy storage or batteries in WSNs, hence extending their operational life when powered by an energy source. Light, kinetics [24, 25, 57], acoustic, thermal [7, 26], wireless, chemical, hybrid, and wind sources were all considered potential energy sources. In terms of ecologically friendly energy harvesting, light harvesting sunlight energy via solar cells is the best option. However, this will rely on the location of the wireless sensor nodes. Energy collection, in particular, has proven to be the most effective method for supplying energy to the wireless sensor nodes monitoring network. Additionally, the environment for energy harvesting is often not harvested in laboratory research, but the application's validity is contingent upon environmental stimulation. Mobility and on-the-ground monitoring are also critical components of energy harvesting assessment systems. Confidential features that also occur when wireless sensor node is used in sensitive energy harvesting environments such as military, aeronautical, medical, or life-critical, require that their functionality be formalised. Specialized assessment methods are critical for guaranteeing the accuracy of data used to certify that energy harvesting can function and work as intended.

1.3 Problem Statement

The primary drawback of wireless sensor node tracker based on GPS are its high-power consumption and the need for renewable energy to extend the lifetime of the system. The emerging concern is that some WSNs equipped with GPS receivers consume more energy and have a shorter lifetime, although, the primary advantage of WSN tracking with GPS is the accuracy. The target sensors are made up of a battery that powers the nodes. These WSN objectives can be accomplished successfully for several weeks or months between battery replacements. The batteries must then be updated or replenished to ensure continued functioning or monitoring for an extended period of time. The primary issue is with compliance applications, regardless of whether the battery must be adjusted daily or weekly due to the requirement for personal security and sensitive activity. On the other hand, a user can extend the life of a WSN tracker by harvesting energy from ambient sources. Additionally, the design and manufacture of WSNs with ultra-low power consumption are regarded key components of the electronic device product flow [69]. The majority of academics and engineers focus on maximising battery life and avoiding excessive battery removal or recharging in order to reduce power consumption, which will extend the lifetime of WSNs [70,71].

Lately, most researchers have designed and developed GPS tracker systems using Arduino and raspberry pi combined with a LoRa shield [34,55,64–68]. However, the prototype GPS tracker's power consumption will be high due to the development board's additional components that are not used by the system. Additionally, the GPS tracker device is more prominent and unsuitable for specific applications, such as animal and human monitoring. On the other hand, the battery size will be increased to enable the object to be tracked for longer. Otherwise, the researchers used a LoRa gateway, which is currently available on the market for transmitting data to a cloud or server [55,64,68]. As a result, this research proposes designing and developing a new GPS tracker with a LoRa-based transceiver device that consumes less power and is smaller in size, measuring 25 x 50 mm. Additionally, this research has resulted in developing a LoRa gateway (base station) with customised communication backbones for data transmission to the cloud or server, including WiFi, GPRS, and an XBee module.

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The lifespan of a battery can be extended by using ambient sources and converting them to charge the battery and energy storage. Some of the potential energy sources are, but not limited to, light [19, 72], kinetics [24, 25, 73, 74], acoustics [62, 75], thermal [26, 76], wireless [77, 78], chemical, wind [8, 51, 62, 73], and hybrid [79]. Light is the recurrent source for environmental energy harvesting, where the solar cells harvest the energy from the sunlight. The development of ultra-low power consumption for WSN is considered an integral part of the electronic system design flow. However, the size of a wireless GPS sensor node proposed appears to be unsuitable for an animal tracker or compliance applications as they are often large [70]. Alternatively, researchers introduced the energy harvesting architecture and associated energy management logic which will be suitable for a portable and inconspicuous tracker. They also addressed the effect of packaging on sensor efficiency and the minimal energy available on GPS monitoring.

1.4 Research Objectives

The aim of the study is to sustain the energy supply on the WSN device for a long term tracking. In order to achieve this aim, specific objectives of this research are stated as follows:

(a) To design and develop hybrid piezoelectric energy harvester and solar for Self Powered - GPS Tracker (SP-GPS Tracker).

(b) To produce the SP-GPS Tracking system consists of SP-GPS Tracker device (transmitter) and base station (receiver).

(c) To analyse and evaluate the optimum performance of the SP-GPS Tracker device, including the piezoelectric hybrid energy harvesting using cars and motorcycles.

(d) To validate the life span of SP-GPS Tracker device between hybrid energy harvesting and conventional battery powered.

1.5 Research Scope

This research aims to design and develop a new LoRa-based GPS sensor node equipped with a hybrid energy harvesting technique (solar and piezoelectric). First, vibration and light will be produced by the moving object. The capacity of the light will affect the amount of solar energy harvested. Vibrations then affect the energy extracted from the piezoelectric transducer. As a result of the sensor node tracking and monitoring the object's movement, this study focuses on hybrid solar-piezoelectric sensors. Second, the SP-GPS Tracker is designed and developed using the Ai-Thinker Ra-02 LoRa transceiver module. The LoRa transceiver module operates at 433, 915, and 868MHz. However, the 433MHz frequency was chosen for this study because the distance between the transmitter and receiver node can be up to ten kilometres in rural areas. On the other hand, the LoRa module's transmit power has been limited to 100mW due to the size constraint imposed by LoRa-based GPS sensor nodes. Thirdly, the Design of Experiment (DOE) Taguchi method is used to determine the optimal design of piezoelectric generators for energy harvesting. Additionally, data were collected experimentally using a frequency-varying vibration shaker. On the other hand, the DOE Taguchi Method compares the optimization design to the experimental data. Finally, the MINITAB software analyses all data collected during the laboratory experiment using a piezoelectric generator using the DOE Taguchi method. Finally, the estimated operating time of the SP-GPS Tracker device were compared when powered by a battery versus when powered by hybrid energy harvesting. Due to the battery's smaller size and lighter weight, the battery type and capacity used to calculate the operation time are Lithium Polymer (LiPo) and 1000 mAh, respectively. The estimated operating time for hybrid energy harvesting, on the other hand, is based on data collected during a field test involving a motorcycle and a car.

1.6 Significance of the Study

Recent research on tracking wireless sensor networks with low power consumption has emphasised the importance of monitoring wireless sensor networks without using a GPS receiver, rather than relying on the WSN's localisation mechanism. However, the primary constraint on this technology is the precision and complexity of the machine. Additionally, previous researchers used single-source energy harvesting to power and track GPS trackers. On the other hand, the energy harvesting application is limited to a specific condition, such as solar or micro-turbine, to power the tracking device. Thus, this work's primary objective is to propose a study to test whether a hybrid energy harvesting system using piezoelectric and solar power can power the SP-GPS Tracker. The maximum energy output from solar energy harvesting has also been studied in indoor and outdoor conditions. According to Wijesundara et al., previous studies have only examined and developed the SP tracker device without energy harvesting or single energy harvesting [80]. The main finding is that combining piezoelectric cylinders energy produces more power than piezoelectric rulers alone.

Most researchers used the DOE Taguchi system to analyse the voltage and power output from piezoelectric energy harvesters [81–83]. The Taguchi research will recommend the best piezoelectric device architecture. However, the researchers solely used COMSOL Multi-physics tools to simulate the piezoelectric plate and device. As a result, the goal of this research has been to build the piezoelectric system to determine the optimum power output and compare the best design. The two alternative designs, ruler and cylinder, were compared in this study. Additionally, the ruler and cylinder designs for the piezoelectric energy harvesting generator have been proposed and analysed to determine the optimal design. Thus, this research argues for using hybrid energy harvesting techniques (such as solar and piezoelectric) to extend the life and performance of an SP-GPS Tracker device. The hybrid energy harvesting technique, on the other hand, is incompatible with wireless, battery-free sensors and devices. Therefore, energy storage was developed and built to provide long-term energy and store enough short-term energy to meet the unique load characteristics of the WSN. Then, using the LoRa transceiver Ai-Thinker Ra-02 module in conjunction with Energy Harvesting, this research enhanced wireless sensor node tracking to achieve ultra-low power consumption for the SP-GPS Tracker device.

On the other hand, the prototype is 50 mm x 25 mm in size and includes a fully functional SP-GPS Tracker device using LoRa transceiver module Ai-Thinker Ra-02. Therefore, the SP-GPS Tracker device power consumption is proportional to the overall power consumption. Finally, a piezoelectric mechanism was constructed using a cylinder and a ruler. The Taguchi method was used to analyse this design to determine the optimal design and size of the piezoelectric energy collecting device. Additionally, the operating time of the SP-GPS Tracker device was estimated when powered by battery or hybrid energy harvesting.

1.7 Thesis Organization

The overall structure of this thesis consist of five chapter, including this introductory chapter. Chapter 2 begins by laying out the literature of the previous method and look at how the energy harvesting help to increase the energy efficiency of the GPS tracker. Chapter 3 is a concern with the methodology used for this study. Chapter 4 discusses the simulation and examine laboratory data of SP-GPS Tracker device's power consumption and hybrid energy harvesting capabilities. The Taguchi approach, which is subsequently utilised to optimise the piezoelectric generator's ruler and cylinder design system discussed in Chapter 5. Chapter 5 examines the calibration of the LoRa module transceiver's power transmission and the power consumption measurement of the SP-GPS Tracker device. Finally, Chapter 7 concludes the research and recommendation for future work.

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LIST OF PUBLICATIONS

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1. **Ismail, M. I. M.** , Dziyauddin, R. A. , Ahmad, R. , Ahmad, N. , Ahmad, N. A., and Hamid, A. M. A.. (2021), A Review of Energy Harvesting in Localization for Wireless Sensor Node Tracking. *IEEE Access Journal*, *9*, 60108-60122. ISSN: 2169-3536, https://doi.org/10.1109/ACCESS.2021.3072061. (**Q1, IF: 3.367**)

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1. **Ismail, M. I. M.**, Dzyauddin, R. A., Samsul, S., Azmi, N. A., Yamada, Y., Yakub, M. F. M., Ahmad, N. A.. An RSSI-based Wireless Sensor Node Localisation using Trilateration and Multilateration Methods for Outdoor Environment. *Cornell University - Journal of electrical engineering and system science - Signal processing* https://arxiv.org/abs/1912.07801.

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2. Azmi, N. A., Samsul, S., **Ismail, M. I. M.**, Dziyauddin, R. A., Yamada, Y., Yakub, M. F. M.. A Survey of Localization using RSSI and TDoA Techniques in Wireless Sensor Network: System Architecture. In *2018 2nd International Conference on Telematics and Future Generation Networks (TAFGEN)*, (pp 131-136). https://doi.org/10.1109/TAFGEN.2018.8580464. **(Indexed by SCOPUS)**