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Energy efficient wearable sensor node for IoT-based fall detection systems

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ABSTRACT

Falls can cause serious traumas such as brain injuries and bone fractures, especially among elderly people. Fear of falling might reduce physical activities resulting in declining social interactions and eventually causing depression. To lessen the effects of a fall, timely delivery of medical treatment can play a vital role. In a similar scenario, an IoT-based wearable system can pave the most promising way to mitigate serious consequences of a fall while providing the convenience of usage. However, to deliver sufficient degree of monitoring and reliability, wearable devices working at the core of fall detection systems are required to work for a prolonged period of time. In this work, we focus on energy efficiency of a wearable sensor node in an Internet-of-Things (IoT) based fall detection system. We propose the design of a tiny, lightweight, flexible and energy efficient wearable device. We investigate different parameters (e.g. sampling rate, communication bus interface, transmission protocol, and transmission rate) impacting on energy consumption of the wearable device. In addition, we provide a comprehensive analysis of energy consumption of the wearable in different configurations and operating conditions. Furthermore, we provide hints (hardware and software) for system designers implementing the optimal wearable device for IoT-based fall detection systems in terms of energy efficiency and high quality of service. The results clearly indicate that the proposed sensor node is novel and energy efficient. In a critical condition, the wearable device can be used continuously for 76 h with a 1000 mAh li-ion battery.

1. Introduction

Fall is one of the most trivial reasons causing traumas and serious injuries (e.g. bone fractures or traumatic brain damages caused by head traumas) [1,2]. Elderly people are likely to fall and they often have more serious consequences after falling than people of other ages. According to statistics, 30% of those over 65 and 50% of those over 80 years old fall every year with hazardous results [1]. Because of high morbidity (almost 20% of fall lead to serious traumas), about 40% of all nursing home admissions are related to fall [3].

Treatment of injuries from a fall often lasts over a long period of time and is very costly (e.g. 30,000 US dollars for a serious case in hospital) [4,5]. The proportion is as follows: 63% of fall-related costs accounts for hospitalizations, 21% is for emergency department visits and 16% is for outpatient visits. However, despite the high significance of the problem, timely aid is only delivered in half of the cases. Unreported cases lead to the deterioration of injury which might complicate treatments later.

Fear of falling amplifies the negative post-fall consequences and might decrease patient's confidence [6]. As a result, it limits the patient's activities, reduces social interactions and eventually causes depression [7,8]. Thus, there is an urgent need of fall detection systems. A quick response to the incident might decrease the risk of serious consequences after a fall. Correspondingly, it helps to reduce treatment costs and to increase chance of recovery. In [9], authors have separated fall detection systems into three groups based on wearable devices, ambiance sensors, and cameras. Systems based on wearable devices seem to be more popular because they can detect a fall more accurately regardless of the patient's location (i.e. indoor and outdoor) and do not interfere the patient's privacy and daily activities. Wearable devices often acquire parameters related to motion such as acceleration, rotation and the direction of motion [10].

It is a challenge for wearable sensor nodes to differentiate between fall events and casual daily activities, or to notify doctors in real-time. Due to their resource constraints (e.g. limited power and storage capacity), it is required to have an advanced system which helps to reduce

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computationally heavy loads on wearable sensor nodes, while maintaining or improving quality of service. Internet-of-Things (IoT) is one of the most suitable candidates for such systems as it consists of a wide range of advanced technologies such as sensing, wireless sensor network and cloud computing for interconnecting virtual objects with physical objects. IoT-based systems can help to reduce wearable devices' burdens by shifting high-computational tasks from wearable devices to their smart gateways. For example, the gateways can perform complex fall detection algorithms (i.e. algorithms based on discrete wavelet transform or data mining). In addition, smart gateways help to improve quality of service by providing advanced services i.e. local storage for storing temporary data or push notification for informing abnormality in real-time.

It is inevitable that IoT can comprehensively help to reduce power consumption of wearable devices by sharing the work load. However, IoT cannot always guarantee a high level of energy efficiency in wearable devices. Other primary issues (i.e. data acquisition and data transmission) causing high energy consumption in wearable sensor nodes must be attentively considered. When a wearable sensor node is energy inefficient, it possibly causes unreliability and reduces quality of service.

In the previous work [11], we have proposed an IoT-based fall detection system. The system comprises of energy efficient sensor nodes, a smart gateway, and a back-end system. The gateway with a Fog layer [12,13] helps to achieve energy efficiency at sensor nodes. In that paper, a sensor node attached to human chest acquires data from a three-dimensional (3-d) accelerometer and transmits the data to the smart gateway via BLE (Bluetooth Low Energy). The main computation (i.e. a customized fall detection algorithm) is performed at the smart gateway since the gateways are powerful in terms of hardware specification and it is supplied by a wall power outlet. The work shows several analysis of primary communication interface buses' power consumption. The results show that SPI (Serial Peripheral interface) consumes less power than I^2C (Inter-Integrated Circuit) and UART (universal asynchronous receiver/transmitter) while SPI's data rates are higher than others (e.g., SPI can support a high data rate of 4 Mbps and more).

The work presented in this paper is a major extension of our recent work published in [11]. In the paper, we aim to study and minimize energy consumption of the wearable sensor node in an IoT-based fall detection system. Furthermore, we analyze undisclosed issues in the previous work. For example, the analysis of advantages and disadvantages of software-based SPI and its impact on energy consumption of a sensor node are presented. Moreover, we analyze energy consumption of the sensor node in various transmission distances and different transmission conditions (e.g. line-of-sight transmission, and transmission via objects). We also investigate and discuss impacts of different sensors (e.g. accelerometer, gyroscope and magnetometer) on both total energy consumption of the sensor node and an accuracy of the fall detection mechanism. We analyze the accuracy of the fall detection system in exceptional cases such as users having abnormal postures. In addition, we discuss and provide comprehensive methods for overcoming limitations (e.g. P2P communication) in the previous work. In this paper, we present the design and implementation of an energy efficient wearable sensor node based on a customized nRF module. The design helps to solve the limitation of P2P communication by offering many-to-many communication between sensor nodes and gateways. Unlike BLE used in the previous work [11] which is connected to the micro-controller via UART, the nRF module in the proposed design uses SPI as its communication bus. Therefore, it incurs a new issue of using several SPI buses simultaneously by a single micro-controller (i.e., SPI communication buses for collecting data from sensors and for transmitting the data via nRF). Therefore, these issues are discussed to find out the most appropriate solution in terms of energy efficiency, feasibility, and complexity. The proposed wearable sensor node is low-cost, lightweight, tiny, energy efficient and flexible. It can be configured to suit to different fall detection algorithms based on motion (e.g. acceleration or angle). The wearable sensor node can provide a viable solution for everyday use without interfering user's daily life. Furthermore, we customize the fall detection algorithm presented in our previous paper for suiting to the proposed sensor node and improving QoS (e.g. the accuracy of the fall detection system).

The rest of the paper is organized as follows: Section 2 includes related work and motivation for this work. Section 3 provides an overview of the IoT-based fall detection system's architecture. Section 4 emphasizes on design principles and reasons behind component and technology selection. Section 5 illustrates the implementation details of the proposed sensor node. Section 6 provides insights about experimental setup and results. Section 7 discusses various issues and findings, and proposes possible solutions. Finally, Section 8 concludes the work.

2. Related work and motivation

Several efforts have been devoted in proposing wearable sensor nodes for fall detection systems. For instance, Casilari et al. use an accelerometer in a smart watch to detect a fall. Accelerometer data is transmitted via BLE from the smart watch to a smart phone which processes data and detects a fall. Then, the smart phone, which acts as a gateway, sends a notification to Cloud via 3G/4G [14]. In another work [15], authors use a depth camera (Kinect) with an accelerometer-based wearable to improve the accuracy of fall detection. Collected data is processed at PandaBoard for detecting a fall in real-time.

Pivato et al. [16] present a wearable wireless sensor node for fall detection. The wearable node whose size is about three times larger than a 2 Euro coin, requires low average current about 15 mA and 25 mA at 50% and 100% duty cycle, respectively. The node is equipped with a 3-d accelerometer ADXL345 and a wireless chip (i.e. CC2420) for gathering and sending acceleration data to a gateway, respectively.

Chen et al. [17] present wearable sensors for a reliable fall detection system. The sensors collect data from low-cost and low-power MEMS accelerometers and send the data via RF. By deploying the sensors at home, the position of the fallen person can be detected.

Biros et al. [18] propose a wearable sensor for a smart household environment. The wearable sensor collects 3-d acceleration and angles from an accelerometer and a gyroscope, respectively. The sensor sends the collected data via ZigBee to Arduino Uno connected to a computer for further processing and detecting a fall.

Erdogan et al. [19] discuss a data mining approach by using k-nearest neighbors for a fall detection system. A wearable device in the system is based on a general purpose board equipped with motion sensors.

In another work [20], the authors present a sensor node based on GSM communication and 3-d accelerometer for a fall detection system. A fall location can be easily detected by the system.

In other works [21,22], authors utilize general purpose boards (e.g. Arduino Uno, Arduino Fio) as the core of fall detection sensor nodes. Although the sensor nodes are low-cost and provide some useful services, they still have several drawbacks such as high power consumption and large physical size. It is known that general purpose boards are often equipped with extra components such as a voltage regulator and a FTDI USB to UART chip ultimately resulting in energy inefficiency.

In several works [14,16–20], fall detection sensor nodes based on motion data often utilizes one or several types of sensors such as accelerometer, gyroscope or magnetometer. The selection of a sensor type or a combination of several sensor types in a single sensor node is mainly focused on functions and features of the sensor(s) while energy consumption of the sensor(s) is not attentively considered. For example, the accelerometer and the gyroscope are often used together in the fall detection applications so as to improve the accuracy of fall detection.

It is known that energy consumption of a sensor node dramatically impacts quality of service. When energy consumption is high, it may