Modular Sensor System (MSS) for Urban Air Pollution Monitoring

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***Abstract*—Air pollution attracts extensive attention globally due to its critical impacts on human life. Monitoring systems providing real-time micro-level pollution information have been developed to provide authorities with data to mitigate these impacts. However, current systems are usually application-specific with fixed hardware and software configurations. They are inconvenient in maintenance, infeasible in reconfiguration, and unexpandable in sensing capabilities. This paper proposes a novel Modular Sensor System (MSS), which aims at tackling these issues by adopting the proposed Universal Sensor Interface (USI) and modular design in a sensor node. A compact MSS senor node with expandable plug-and-play sensor modules and multiple Wireless Sensor Networks (WSNs) compatibility is implemented and evaluated. Results indicate that MSS sensor node can be deployed in different scenarios while dynamically adapting to reconfigurations and monitoring air pollution at low concentration levels with high energy efficiency. We anticipate that MSS is able to relax the efforts on system maintenance, adaptation, and evolution in real-life large-scale deployment situation.**

***Index Terms*—air pollution monitoring; wireless sensor network; modular sensor node; plug-and-play**

I. Introduction

Air pollution attracts extensive attention worldwide due to its tremendous impacts on human health, global environment and economy [1], [2]. Conventional monitoring systems have been deployed to provide authorized information for urban management and environmental improvement. These systems have extremely low spatial and temporal resolutions [3] and are inadequate for monitoring personal and acute exposures to air pollutants [4], [5].

Thanks to the advance in technology, real-time air pollution information with high spatio-temporal resolution and in-time personal acute exposure warnings are available in next generation air monitoring systems [6] by deploying large numbers of stationary, wearable, or vehicular sensor nodes in field.

However, state-of-the-art systems providing real-time micro-level air pollution information are usually application-specific with fixed hardware and software configurations [7], [8], [9], [10]. Their flexibilities in maintenance, reconfiguration, and deployment are limited. In this paper, a Modular Sensor System (MSS) is proposed to address these issues. The major contributions of this paper are:

- A Modular Sensor System (MSS) architecture with configurable sensing capability, multiple WSNs compatibility, and reconfiguration adaptability;
- A Universal Sensor Interface (USI) enabling modular design in hardware/software, energy efficiency, configurable sensing capability, and reconfiguration adaptability;
- Design, implementation, and evaluation of a compact MSS senor node with 6 plug-and-play sensor modules and multiple WSNs compatibility, which is easy to use and maintain, and can be conveniently reconfigured for different monitoring scenarios.

The remainder of this paper is organized as follows. In Section II, the proposed MSS architecture and its implementation are presented. A MSS sensor node is evaluated in Section III. Section IV presents the conclusion of this paper.

II. System Architecture and Implementation

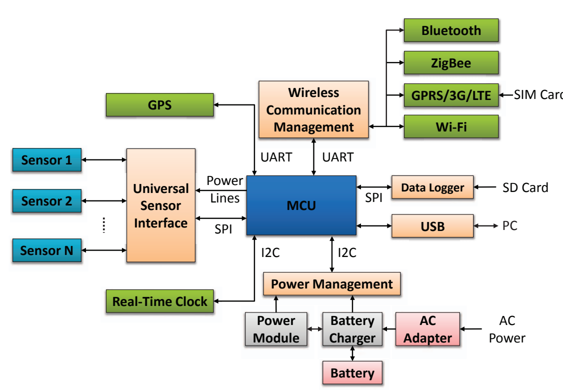

Fig. 1. System architecture of a MSS sensor node.

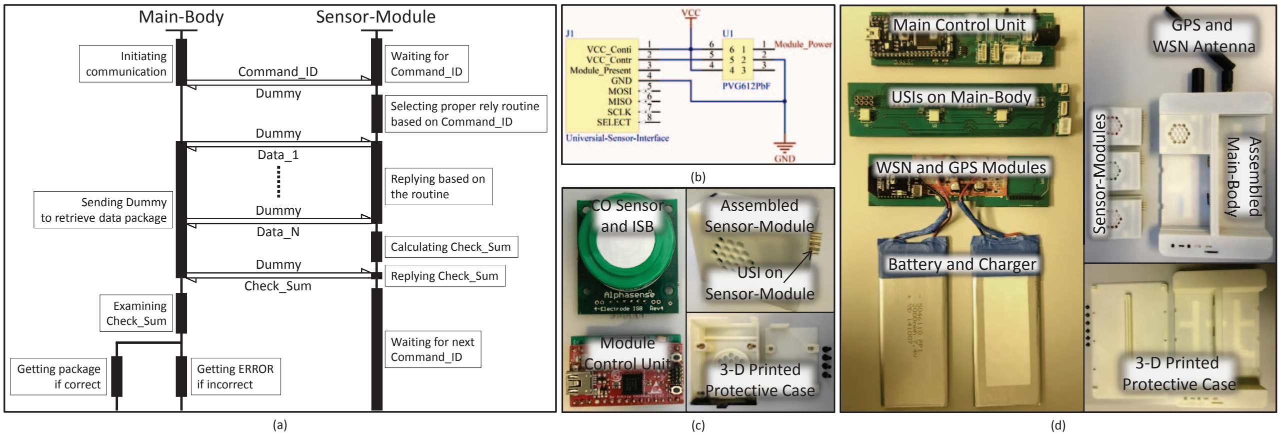

Fig. 2. (a) Timing diagram of USI's communication protocol. (b) Schematics of USI on Main-Body. (c) Assembled Sensor-Module. (d) Assembled Main-Body

In this section, the proposed Modular Sensor System (MSS) architecture design, including the Universal Sensor Interface (USI), and the detailed implementation are presented.

A. System Architecture Design

The system architecture design of MSS is illustrated in Figure 1. Each sensor is connected to the microcontroller (MCU) through the proposed USI. Multiple sensors on-board ability, configurable sensing capability, and dynamic reconfiguration adaptability are enabled by the USI. Also, a low-footprint SPI based protocol, which is essential to dynamic reconfiguration adaptability, is adopted for communication between sensors and MCU. Power lines of sensors are controlled by the MCU for power management, detection maximizing, and fault tolerance purposes.

A GPS and a real-time clock modules are used to tag location and time information to sensing data respectively. Multiple WSN modules (Bluetooth, ZigBee, GPRS, Wi-Fi, *etc.*) are supported by the wireless communication manager, which ensures the network-connectivity and cost-efficiency of sensor nodes in different kinds (stationary, wearable, or vehicular) of deployment scenarios. A data logger, a USB port, and a battery power system are utilized for data recording, debugging, and power management purposes respectively.

B. Detailed Implementation

A sensor node adopting the proposed MSS architecture is decomposed into two subsystems, namely Main-Body and Senor-Module.

1) Main-Body Subsystem: As illustrated in Figure 2d, it consists of six USIs, a main control unit, a WSN and a GPS modules, and a 3-D printed protective case. Main-Body is able to support up to sixteen Sensor-Modules.

The schematics of a USI on Main-Body is shown in Figure 2b. J1 is the 8-pin connector of USI. VCC_Conti powers components in Sensor-Module that require continual power. Controlled by main control unit using signal Module_Power on relay U1, VCC_contr powers the module control unit in Sensor-Module for purposes mentioned in Section II-A. Module_Present is driven low to notify the main control unit whenever a Sensor-Module is inserted. It is essential for the configurable sensing capability and dynamic reconfiguration adaptability. MOSI, MISO, SCLK, and SELECT are standard pins for SPI communication. A low-footprint SPI based communication protocol between Main-Body and Sensor-Module is implemented and its timing diagram is presented in Figure 2a. A Mbed LPC1768 MCU, a real-time clock IC, and a MicroSD card based data logger are utilized in the main control unit. Multiple sensors are supported by using three 16-bit IO expanders to control signals Module_Power, SELECT, and Module_Present on USIs respectively. Because Xbee footprint is adopted, any Xbee packaged WSB modules can be applied in Main-Body.

2) Sensor-Module Subsystem: For illustration purpose, a CO Sensor-Module as illustrated in Figure 2c is presented. In fact, enabled by MSS and USI, any sensors satisfying the physical constraints (size, weight, power, *etc.*) can be adopted.

The Alphasense B4 series electrochemical CO sensor and it supporting circuit (ISB) are selected because they can measure CO with ppb-level resolution and mW-level power consumption. The CO sensor and ISB are powered by VCC_Conti continuously and the module control unit (Mbed LPC11U35 MCU and other devices) is powered by VCC_Contr in every sensing interval. Such mechanism ensures high energy efficiency and good data quality simultaneously because the sensor require stabilization time (about 2h) every time after switching on. Due to page limitation, discussions on selection of sensor, voltage regulator, ADC, *etc.*, are omitted.

III. Evaluation

In this section, a CO Sensor-Module is plugged into the Main-Body for evaluation. Experiments including comparisons between MSS and existing systems, data acquisition, and data visualization are performed.

First of all, comparisons between MSS and four existing systems are performed as shown in Table I. Outstanding abilities like configurable sensor number and types, multiple

TABLE I
COMPARISON OF DIFFERENT SENSOR NODE SYSTEMS.

System	Sensor Number	Sensor Type	WSN Type	Deployment Scenario
[7]	3 or 5	O_3, NO_2, CO, etc.	GPRS	Stationary
[8]	5	temperature, humidity, pressure, etc.	Wi-Fi	Stationary
[9]	4	CO_2, light, humidity, etc.	Bluetooth	Wearable
[10]	1	O_3	None (cable)	Wearable
MSS	Configurable (max. 16)	Configurable and Expandable	Bluetooth, GPRS, Wi-Fi, Zigbee, etc.	Stationary, Wearable, Vehicular

WSNs compatibility, etc., differentiate MSS from existing systems.

Secondly, the MSS sensor node is connected to a PC through USB for data collection as shown in Figure 3. Main-Body successfully identified the Sensor-Module inserted and selected proper handling schema. In this experiment, the data acquisition rate is 5 seconds and the sensor node is placed next to the university road. The first four peaks were recorded right after the campus shuttle buses passing by. This indicates that real-time, low-concentration air pollution information can be captured by the sensor node and in-time personal acute exposure warnings can be achieved.

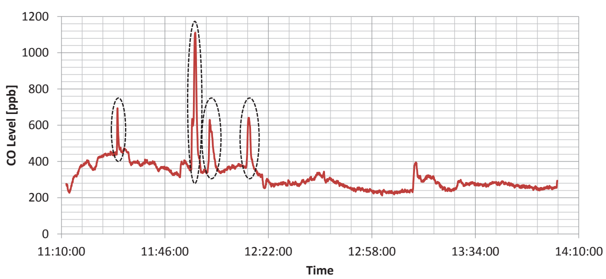

Fig. 3. CO concentration over time. (Data were collected from 11:11:40 to 14:02:30 in April 27th, 2016. The first four peaks were captured right after the campus shuttle buses passing by.)

Thirdly, an Android App is also implemented for receiving data from the MSS sensor node through Bluetooth and latter transmitting the data to the data sink through cellular network. The screen shots of the App are shown in Figure 4.

IV. CONCLUSION

In this paper, a Modular Sensor System (MSS) architecture, including a Universal Sensor Interface (USI), is proposed to address the fixed hardware/software configuration issue of state-of-the-art air pollution monitoring systems. A MSS sensor node with 6 plug-and-play sensor modules and multiple WSNs compatibility is designed, implemented, and evaluate. Results indicate that MSS sensor node can be deployed in different scenarios while dynamically adapting to reconfigurations and monitoring air pollution at low concentration levels with high energy efficiency. We anticipate that the proposed MSS is able

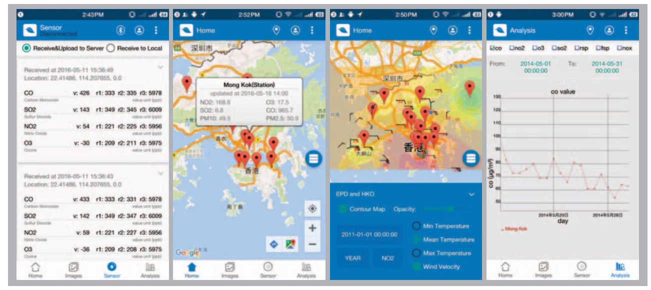

Fig. 4. Screen shots of the Android App. (The first sub-figure shows data collected by the MSS sensor node. The remaining sub-figures are some other features of this App which is part of an ongoing project in Institute of Future City, The Chinese University of Hong Kong.)

to relax the efforts on system maintenance, adaptation and evolution in real-life large-scale deployment situation.

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