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Research Article

Prototype Design of Smart Greenhouse Gases Systems for Environmental Monitoring in Peatland Areas

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Abstract

Monitoring atmospheric greenhouse gases emissions in peatlands are increasingly important to anticipate the causes of fires and their impact on the environment. This study has designed a prototype GHG monitoring system for tropical peatlands using Netduino 3 Wi-Fi and is connected to meteorological sensors. The application systems developed with C# can access measurements remotely through the Internet of Things platform. The smart monitoring system has the advantage to measure new parameters such as precipitable water vapor and water vapor concentration rather than originally only measuring surface pressure, temperature, and relative humidity. It also can send measurement results and store data to micro secure digital and two web servers (Google Form and Dropbox). In the first stage, the prototype was tested in two conditions: inside and outside the laboratory before being installed on peatlands. The result of the measurement system has also been compared with CO_2 levels and CH_4 levels measured from NDIR gas sensors.

Keywords: Prototype, Smart systems, Internet of Things, Greenhouse gases, Peatlands

1. **Introduction**

Research on reducing greenhouse gases (GHG) emissions from peatlands and forests has recently been intensively carried out but is still limited to access land. Gas emissions from peatlands or forests can release large amounts of carbon into the atmosphere, especially during the dry season or El Niño event [1]. Van Lent et al. [2] highlighted that GHG emissions released by peat into the atmosphere primarily consisted of carbon dioxide (CO_2), methane (CH_4), and Nitrous oxide (N_2O). GHGs stored in the earth's atmosphere play an important role in weather and climate mitigation, especially in the affected areas. On the other hand, the triggers of fire in the natural forest are much different from man-made fires in oil palm plantations. In prolonged dry seasons, soil that clutching at forest roots can ignite itself, meaning that very dry soil has the potential to have a very high carbon content. Censequently, the amount of GHG released into the atmosphere increases significantly due to changes in peat soil ingredients. Due to these complicating factors, measurement of GHG emissions including moisture content in peatlands is necessary to mitigate local impacts. Efforts in this direction allowed possibly to optimize existing resources and expect the reduction of these gases to remain at a safe level below 1.5%, as determined by the Environmental Protection Agency (EPA) [3]. In addition, existing in-situ environmental monitoring systems such as forest fire systems still have limitations in detecting changes in GHG emissions although they have used a wireless sensor network (WSN) [4, 5]. Satellite-based imaging can detect hotspots over a large area but smoke can interfere with the satellite's ability to detect fires [6, 7].

Many gas sensors have been produced for environmental monitoring but environmental characteristics and the need of intelligent monitoring are new challenges. Beirne et al. [8] have developed an autonomous gas sensing to monitor GHG produced by landfill sites. They placed four sensors in the prototype including temperature, relative humidity, and two infrared CO_2 and CH_4 sensors to measure the surrounding environment. The prototype equipped with short-range (Bluetooth) and Global System for Mobile communication (GSM) modules to harvest data from a remote base station. Jaichandran and Irudhayarj [9] has also developed a prototype for monitoring and computing GHG parameters (like CO_2, CO, temperature, and humidity) which using ARM microcontroller and XBee pro wireless module. With the same purpose, Collins et al. [10] have also developed an autonomous remote gas sensing with web-based accessibility where two infrared sensors are assembled to sense the concentration of CO_2 and CH_4. They used a custom-programmed microcontroller from Texas Instruments to control all the processes in this system. The latest in-situ GHG monitoring systems is developed by the UK Deriving Emissions linked to Climate Change (UK DECC) [11]. This measurement system equipped with automated alert provides a convenient platform for boundary layer trace gas sampling. This network provides good spatial and temporal coverage of atmospheric mixing ratios within the UK but it is not specifically applied to peatlands. Suparta et al. [12] have also developed a low-cost portable automatic weather station using Arduino Uno and BME280 sensors to measure PWV on a micro-scale but cannot be used for long-term and permanent measurements in the forest.

To deal with the challenges above, the present work is to propose the development of a prtototype for environmental

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monitoring that uses a Netduino and meteorological sensors connected via wireless transmission to monitor GHG concentrations such as water vapor and gas emissions released from Peatlands. The meteorological sensors are capable of measuring surface pressure (P), temperature (T), and relative humidity (RH). The three parameters will be employed as a proxy to measure GHG, which is so-called precipitable water vapor (PWV). PWV is computed using the adaptive neuro-fuzzy inference system (ANFIS) techniques with P, T, and RH as inputs. In other words, PWV is a GHG parameter consisting of CO_2 and other gas components where the trend increases with global warming. To get more details about the computation of PWV using ANFIS, readers are advised to refer to Suparta and Alhasa [13]. In particular, this paper focuses on hardware design and development of application systems (Apps) by employing the Internet of Things (IoT) and wireless transmission systems. These devices have a unique identity to communicate via a wireless transmission with advantages in the distribution of data, ease of install, and flexible movement [14]. This work starts with selecting hardware devices and building several modules to support the proposed system. The main hardware developed will be integrated electronically with Apps. The code in Apps is developed using C# programming and then embedded into the Netduino as a knowledge base to perform data acquisition and data processing. The final target of the system built is being able to generate automatic alerts and send a notification to site operators via email or SMS.

Furthermore, a water vapor concentration (WP) will also compute for the comparison of PWV values. WP obtained from water vapor mixing ratio is defined as the mass of water vapor per mass of dry air which shows gas constituents [15]. If the measured gas concentration (like CO_2 and CH_4) correlates well with PWV results, the final hardware required for our monitoring systems on peatlands is only meteorological sensors with Netduino. To evaluate the system performance, the result of the gas emission from meteorological sensors is also compared with CO_2 levels and CH_4 levels measured from Non-Dispersive Infrared (NDIR) gas sensors. Finally, before the system is installed on peatland, its performance should be tested and validated.

2. Materials and methods

2.1 Prototype design of smart GHG monitoring systems

This section presents a detailed prototype designed consisting of hardware conceptual design, sensor selection, and electronic design. Several hardware modules are developed to support the overall system together with Apps architecture as the main support in the development of smart systems.

2.1.1 Module designed for smart GHG monitoring systems

The core device of the GHG monitoring system is run by a microcontroller embedded in the Netduino 3 Wi-Fi. The microcontroller initializes all the key actions that must be performed for the entire system. There are four main components integrated lead the system to work autonomously, namely the sensing unit, processing and storage units, transmission, and power supply. The sensing unit consists of meteorological sensors and gas sensors. The meteorological sensors represent P, T, and RH, while gas emission sensors will measure the concentration of CO_2 and CH_4. The microcontroller has been equipped with a CC3100MOD wireless module from Texas Instruments to control processing and storage unit as well as data transmission. The last part is solar energy and a 12V battery integrated as a power supply unit. Fig. 1 shows the module architecture built as a smart GHG monitoring system for peatland areas. Fig. 1(a) shows the connection between the modules and the microcontroller (Netduino 3 Wi-Fi) while Fig. 1(b) shows the input and output of the overall system.

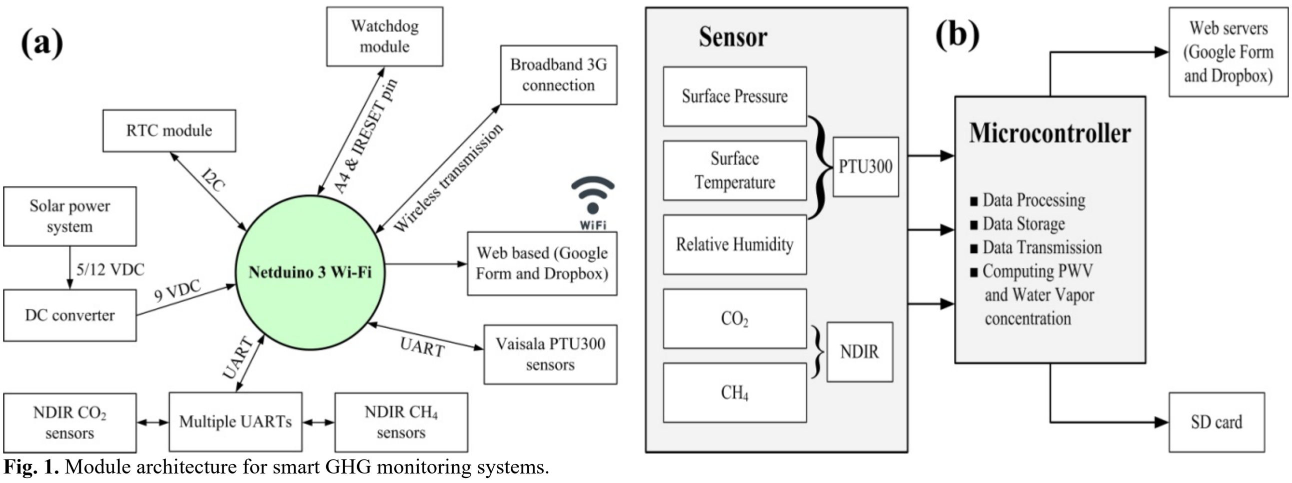

Fig. 1. Module architecture for smart GHG monitoring systems.

2.1.2 Module selection

The selection of modules to be integrated to develop a prototype GHG system such as sensors and microcontroller considers costs, environmental conditions, and maintenance. Specifically, the advantages of selecting this system are matched with laboratory standards, low-cost, easy to obtain, and operated permanently for long-terms. The following is a brief explanation of the hardware selection.

a). Netduino

Minicomputers or laptops cannot be installed in this peat area because they are prone to break-ins and if the computer is shutdown it cannot be handled remotely. Instead, Netduino-based microcontrollers are selected. Netduino is designed to be plug-compatible with Arduino shield and is customized to run on the .Net Micro-Architecture Framework. It has the advantage of being easily programmable and flexible in interfacing. In this work, Netduino 3 Wi-Fi (hereinafter referred to as Netduino) is used as smart control of the GHG monitoring system. The main difference between Netduino 3

Wi-Fi with previous models such as Netduino 2 plus is that the Ethernet port on the previous model has been replaced with Wi-Fi (2.4 GHz 802.11b/g/n via TI's CC3100). This allows online connections to be easier and more flexible. With improved specifications, the latest Netduino can run faster and it has more space to write an application.

b). Surface meteorological sensors

PTU300 sensors from Vaisala have been selected to measure surface meteorological parameters (P, T, and RH). The accuracy and specification of this sensor can be found at the https://www.vaisala.com/.

c). Gas sensors

In this work, NDIR sensors are selected due to a practical way to measure gas concentrations in the air as well as cost-effective [15]. In our system, two types of NDIR sensors are used to measure CO_2 and CH_4 concentrations. Both sensors are allowed to collect data via digital and analog outputs, and pre-calibrated by the manufacturer. The main purpose of using gas sensors in this work is to validate the PWV values obtained from meteorological sensors.

d). Power supply

A careful selection of power supply for remote areas is very important to run the system continuously for 24 hours. Solar energy with portable solar PPS70 is used to power the GHG monitoring system [16]. Our system required a voltage in the range of 12 V ± 10 percent. If the battery has dropped to 10.8 V, it will recharge automatically and stops when the battery voltage reaches 13.2 V. The power system is also capable to prevent reverse current flow back through the solar panels at night when the power supply fails.

2.2 Electronic Design

To support the main components of the smart GHG monitoring system, the electronic component design is divided into five modules, i.e. (a) real-time clock (RTC), (b) RS232 to universal asynchronous receivers/transmitters (UART), (c) multiple UART channels modules, (d) watchdog timer, and (e) DC converter as presented in Fig. 2.

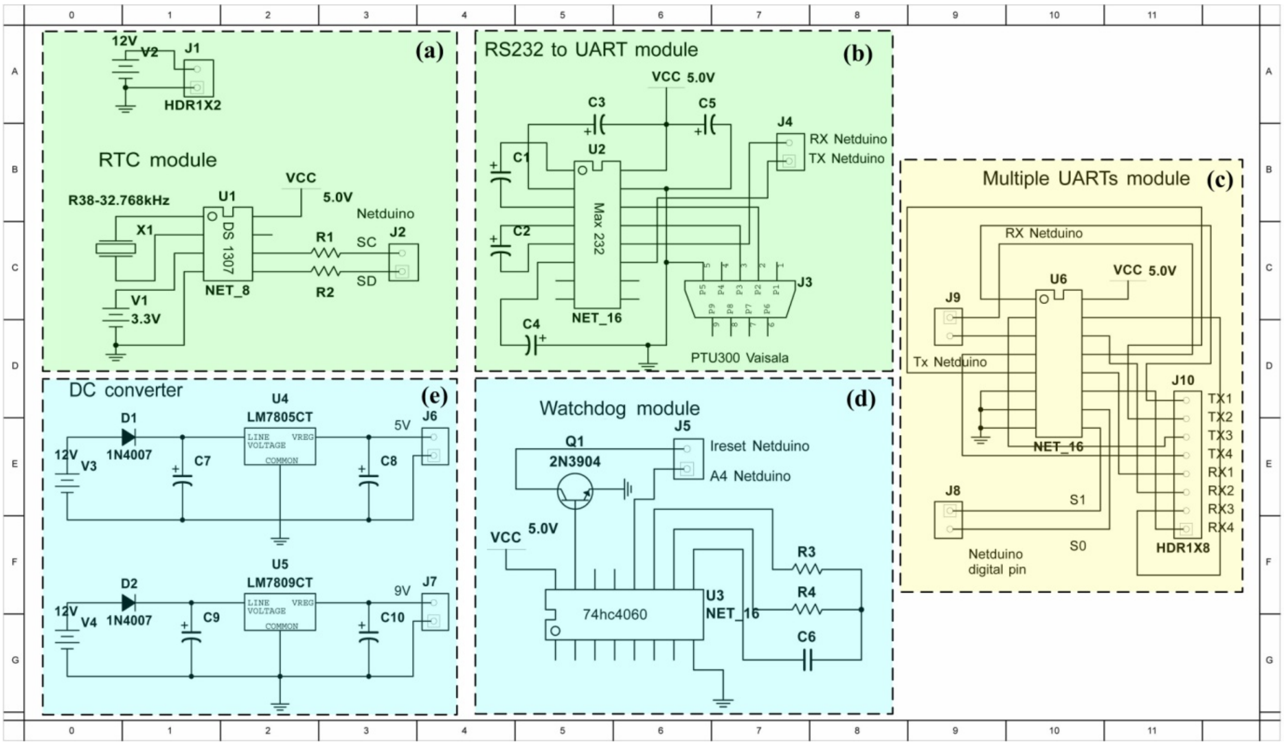

Fig. 2. Module architecture for smart GHG monitoring systems.

Each module in a clockwise direction is explained as follows.

a). RTC module

For data loggers, time and date are important elements to indicate the accuracy of measurement during the acquisition process. Since Netduino their internal clock faces an error or resets when returned to the original settings, a Real-Time Clock (RTC) module is developed to provide a precise time and date during the acquisition process as well as to keeps track of time and date continuously although the power supply is reset. A DS1307 IC from MAXIM, two 10 kΩ pull-up resistors, a crystal clock, and a CR-2025 3V lithium battery are used to build the RTC module (see Fig. 2a). The RTC can be connected to Netduino via I2C (Inter-Integrated Circuit). I2C serves as a carrier of information from and/or to a controller via a serial bus communication protocol that uses two wires serial interface includes serial data (SDA) and serial clock (SCL).

b). RS232 to UART module

PTU300 sensors are well communicated with other instruments via the RS232 serial interface. However, the signal between RS232 and Netduino pins and vice versa (±3V to ±25V) is unsynchronized. This problem is solved by placing an IC of MAX232 to invert the RS232 voltage level to the appropriate transistor-transistor logic (TTL) voltage level (see Fig. 2b).

c). Multiple UART channels module

Due to the Netduino only equipped with four UART channels where two UARTs has been used for I2C serial bus communication (UART 4) and Pulse-Width Modulation (PWM) (UART 2), respectively. Multiple UART modules are required to put three more sensors simultaneously in this system. A 74HC4052 IC is used as multiplexer and demultiplexer methods to construct a multiple UART module (see Fig. 2c). In this module, selection input pins are connected to a digital pin on the Netduino board to get a voltage level (High or Low), while T_X and R_X pins are connected to the common input.

d). Watchdog timer module

Since the system will be placed in remote areas and Watchdog from most microcontrollers cannot support the firmware of Netduino, a "Watchdog" timer which functions as self-recovery from unexpected halts is developed. A Watchdog timer module is constructed using a 74HC4060 IC counter and embedded by the R-C oscillator as a threshold time and NPN transistor as a switching circuit (see Fig. 2d). This external "Watchdog" will reset the microcontroller if it does not receive a signal from the microcontroller within a specific time. On the other hand, the output of Q9 in 74HC4060 was selected as a timeout signal, which triggers the Netduino reset or Q9 pin should not reach or changes to high.

e). DC converter

A DC converter module has also been developed to equal the voltage required by Netduino and other components (see Fig. 2e). This module stabilizes the system for running 24 hours continuously.

2.2 Application Design

The routine of the application system (hereinafter referred to as Apps) is written in C# which applies the concept of object-oriented programming (OOP). This concept correspondence with the .Net Micro-Architecture Framework which allows Netduino to carry out multithreading processes where main routines and subroutines are run simultaneously. Several subroutines and two additional threads are developed to facilitate programming and save processing time. Part of subroutines are serial communication, switching channels, computation of PWV and WP, storage device, append filling, and handling errors, while additional threads are Google Drive and Dropbox classes. Overall, the main key to executing these Apps is the Wi-Fi connection (e.g. via 3G communication).

2.2.1 Development of main threads

The main thread in this Apps has three tasks: collecting, computation of PWV and WP, and data monitoring. The main routine starts with a configuration system, followed by collection, computation, and storage. The surface meteorological sensors and gas sensors served as inputs to measure GHG emissions (see Fig. 1b). Sensors in each UARTs channel collecting data in 5s interval. This interval is selected after considering the response time for each sensor in the UART module as well as to avoid conflicts between the channels. To collect data, the Apps should send a command on how to get permission to retrieve data from the sensors. In this thread, the data package received from sensors is in byte format and then converted to string format for readability.

After performing data collection, the main thread will go into the computation of PWV and WP through the ANFIS PWV class and the WP class, respectively. By using the ANFIS model to compute PWV, the input of surface meteorological data must be transformed into fuzzy values [13]. Once transformed, these values will be evaluated using a rule-based and knowledge base provided in this class. The output of this stage will be used as a parameter in the form of a linear equation (defuzzification process). Finally, PWV is obtained from the summation of the defuzzification process. On the other hand, the WP value is obtained from a ratio of molecular weight of water vapor to dry air (ε), surface pressure (P), and partial pressure of water vapor (P_w) as given by [15, 18-19].

$$WP = \varepsilon \frac{P_w}{P - P_w} \quad (1)$$

where ε is contant (the ratio of the molecular weights of water vapor (18) and the average molecular weight of dry air (28.9) = 0.622), P_w is obtained from the relative humidity (RH), and saturation vapor pressure (e_w) for water as recommended by World Meteorological Organization (WMO) [20] and given by

$$P_w = \frac{RH}{100} \times e_w \quad \text{where} \quad e_w = 6.112\, exp^{\left(\frac{17.62T}{243.12+T}\right)} \quad (2)$$

where all units for pressure are in mbar, T is the surface temperature in degree Celsius, and e_w is derived from the Magnus equation. The unit of water vapor concentration in this work is in kg per kg or equal to 10^6 ppm (part per million). The next task is to arrange and store all the existing parameters before being sent to the data center. The time stamp produced by RTC class is used as a time and date marker. All collected data is averaged every one-minute to reduce data storage load. Each recorded data contains one single file per day with a sequence format of Year, Date, and Month (YYYYDDMM.txt). This format is for easy indexing of files during the recording process. In addition, an append filling technique is applied to prevent the existing file from being overwritten by new files when the electricity is recovered from unexpected halts. By this technique, a new file will not be created on the same day. Every one-minute the data will be sent to SD card and Google Form, while the data that has been stored on the SD card is sent every 5-minute to Dropbox. Fig. 3 describes the block diagram of the Apps main routine in the development of prototype GHG monitoring systems.

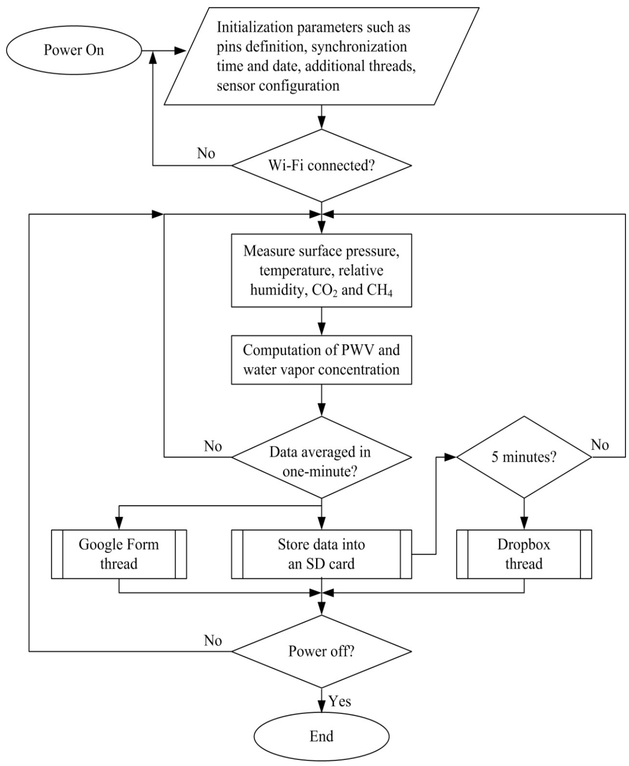

Fig. 3. The main thread Apps flow diagram.

2.2.2 Development of additional threads

Two additional threads will be developed in this Apps to upload the data to a web server. Two web servers (Google Form and Dropbox) are used with different tasks. The Google Form is used to store data from direct measurements, while Dropbox has the task of uploading data stored from the SD card. To upload data for users, the Hypertext Transfer Protocol (HTTP) request method is used to construct all parameters including option method, host, content-application, and content-length of data. This is required to connect Apps with web servers. Fig. 4 shows a flow diagram of two additional threads developed.

For the Google Form (see Fig. 4a), the parameter constructed in the anatomy of call functions via HTTP requests method are POST (http://docs.google.com) and HOST for content-application (application/x-www-form-URL encoded), respectively. A POST request is used to send data to the server, while the HOST placed in the header is to specify which web server to be used. Unique keys associated with “text fields” and URL “form Response” in Google Form are used as “entry_ID” to load the data. Each "text field" has a different unique key available in the source code page of Google form Apps. Google Spreadsheets can be used to access data submitted into Google Form. Data is displayed in a tabular form where the first line is a header that represents the identity of each measured parameter.

For Dropbox (see Fig. 4b), it has a different construction and access permissions, which are called “Token”. A “Token” can be obtained if Apps already has identities such as “username” and “app secret”. In the anatomical construction of the HTTP request method, a “Token” is placed in the header, which is known as “Header Authorization”. It contains specific information about the status of Apps which has the authority to access and load files into Dropbox. The header also contains the path of the folder that serves as the destination address for placing the file. Failure in the upload process can occur if there are errors in writing the address. Files uploaded to Dropbox have a similar structure to files stored on an SD card.

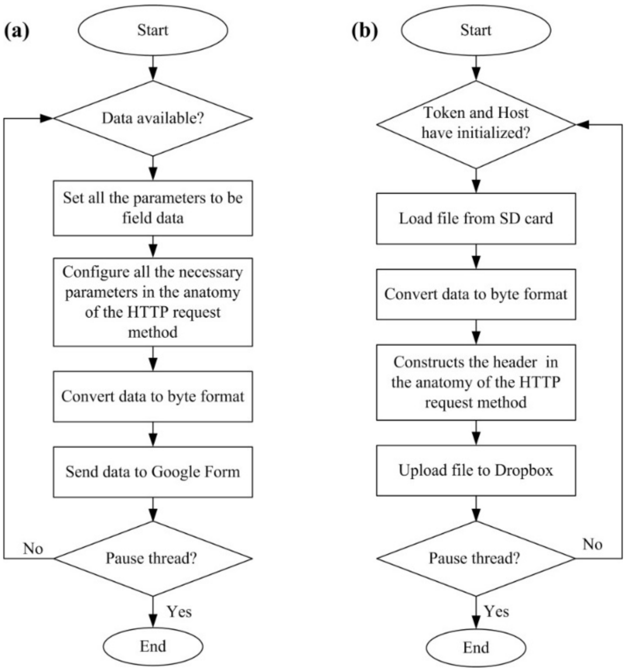

Fig. 4. Flow diagram additional threads for (a) Google Form and (b) Dropbox.

3. Results

3.1 Prototype for monitoring system

The result of this research is a prototype of GHG monitoring for peatlands as shown in Fig. 5 where all the developed modules are placed on a single layer printed circuit board (PCB). The PCB layout is Do It Yourself (DIY). In each PCB consist of (a) multiple UART channels, (b) RTC and DC converter, and (c) Watchdog and RS232 to UART. Overall, the complete prototype of the smart GHG monitoring system is presented in Fig. 6 where Figs. 6a and 6b show components or devices that have been assembled (inside) and outside the box, respectively. In other words, the results presented in this section are a ready-to-use prototype system for GHG monitoring.

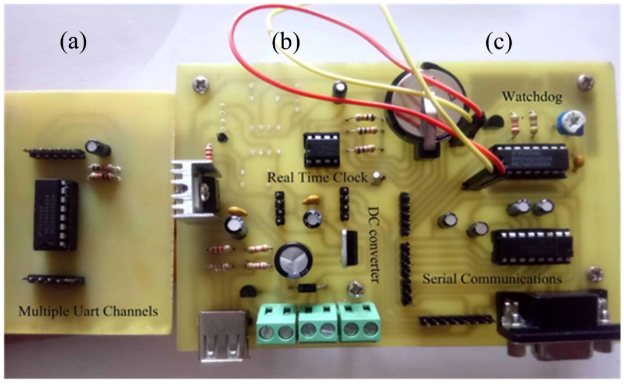

Fig. 5. All developed modules are mounted on the PCB by DIY (Do It Yourself).

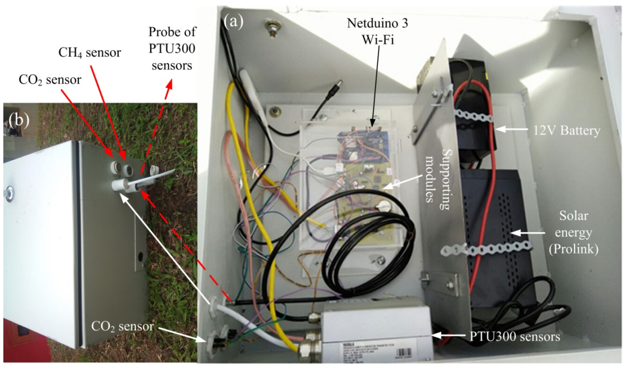

Fig. 6. The prototype of a smart GHG monitoring system.

3.2 Apps for data loggers

By implementing Apps (additional threads), Fig. 7a shows an example of data and that was succeeded collected and stored on Google Form which contain date, time, surface pressure (mbar), surface temperature (°C), relative humidity (%), and PWV (mm), whereas WP (ppm), CO_2 (ppm), and CH_4 (%) on the right side of spreadsheets are not captured but are shown in Fig. 7b. In the file, data are missing or errors at the 10th row when the setting time is not set to 5 s. This error was rectified through the development of the Watchdog time module. On average, the daily file size stored to the SD card with seven parameters (see the screenshot of Fig. 7b) is approximately 98 KB. The data stored on the web server is in the same format as in a text file. An example is one the files from the screenshot in Fig. 7b where the data collected is for 23 April 2016.

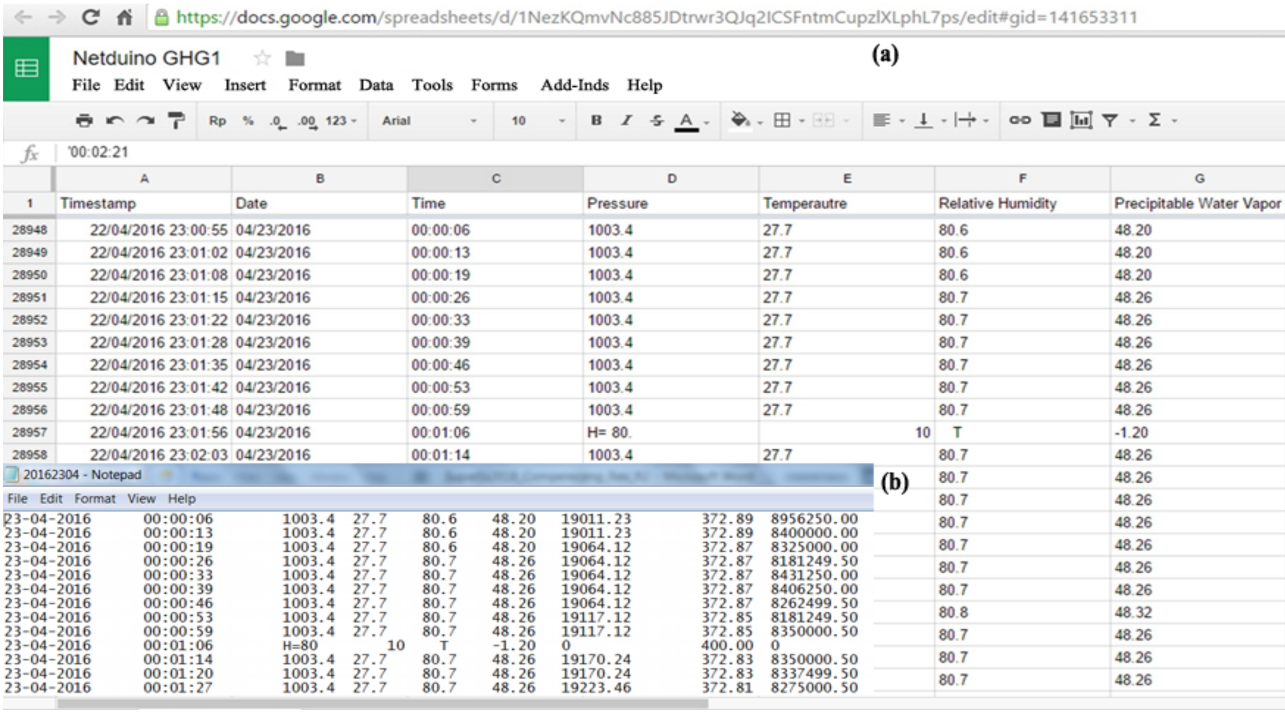

Fig. 7. An example data stored in (a) Google Form and (b) SD card.

3.3 Testing system

The performance of the GHG monitoring system needs to be tested to prevent installation failure on the destination site. Several experiments have been carried out based on the equipment in Fig. 4. One of the reports in this paper is the result of five days of testing (see Figs. 8 and 9). Two test conditions are carried out including inside and outside the laboratory. Inside the laboratory (see Fig. 8), the system is placed in the room where the surrounding containing several instrumentations and people who working there. The system has measured WP as well as CO_2 and CH_4 emissions in the room. For CH_4 concentration, the unit has been converted to ppm by multiplying 10000. As shown in the figure, the system starts running at 14.00 LT. The pattern of CO_2 concentration has the opposite shape compared to the PWV and WP. The CO_2 has the strongest negative Pearson correlation (r) of -0.90 and -0.89 for PWV and WP, respectively, significantly at the 99% confidence level. During the day it looks higher because many people are working indoors and it gradually decreases and is constant after people leave. The trend of PWV and WP shows a linear relationship following changes in temperature. In conclusion, the indoor system did not detect any CH4 concentration or zero as shown in the last panel of Fig. 8.

For the testing outside the laboratory, it was carried out on the roof of the Research Complex Building of Universiti Kebangsaan Malaysia (UKM). This place is beneath the open sky and surrounding by several buildings and small forests. Fig. 9 shows the PWV and WP have a similar pattern to RH. Both showed an increase in the morning until before noon, a gradual decrease in the afternoon, and a gradual increase until nighttime. The CO_2 and CH_4 have a similar pattern but CO_2 concentration has a constant value of about 400 ppm from noon to night. This happens because of many trees surrounding the UKM environment will release the amount of CO_2 in the nighttime and absorb CO_2 in the noon as the source of photosynthesis. Based on the comparison between both of water vapor content (PWV and WP), CO_2 and CH_4 concentrations, we can state that during the late midnight when the concentration of CO_2 is high (400 ~ 500 ppm), both are equal to 50 mm and 18,000 ppm in the normal air, respectively. At this time, our CO_2 concentration is comparable with CO_2 at Mauna Loa Laboratory where the global weekly mean shows 400 ~ 420 ppm (https://www.esrl.noaa.gov/gmd/ccgg/trends/). On the other hand, when CO_2 is a constant (400 ppm), it will equal 42 mm of PWV on average. During no CO_2 concentration recorded or below 400 ppm, the sensor gives 400 ppm readings. This 400 ppm is the lowest value possessed by the sensor used for testing. Focusing on the CH_4 concentration (3,000 ~ 6,000 ppm or two times larger than global mean), variations in PWV and WP are observed similar to CO_2, where their averages are about 45 mm and 1,800 ppm, respectively. At this point, depending on environmental conditions, the relationship between moisture content and trace gas is positively correlated. In other words, the gas sensors and meteorological sensors in this experiment show compatibility with each other.

In this research, the main considerations in building the system were the cost and location of measurement agreed to place the instrument permanently. After conducting several site surveys with the authorities, finally, we have succeeded in building a prototype GHG monitoring system as shown in Fig. 4. Before the system was installed in the agreed sites, the outside experimental test was carried out on the UKM Campus, and found that PWV and WP on averages showed positively correlated with CO_2 and CH_4 concentrations. Under normal conditions, PWV is obtained in the ranges from 40 ~ 50 mm and CO_2 ranges from 400 ~ 450 ppm. This confirms that the largest component of water vapor is GHGs such as CO_2 and CH_4, and hints that the prototype is ready to be installed on peatlands. The real-time measurements connected via 3G will also allow users to easily access the data from systems. Note that the sensitivity of the present system in detecting CO_2 concentrations using NDIR is with a default value of 400 ppm. This means that when no detected for CO_2, the reading will be 400 ppm.

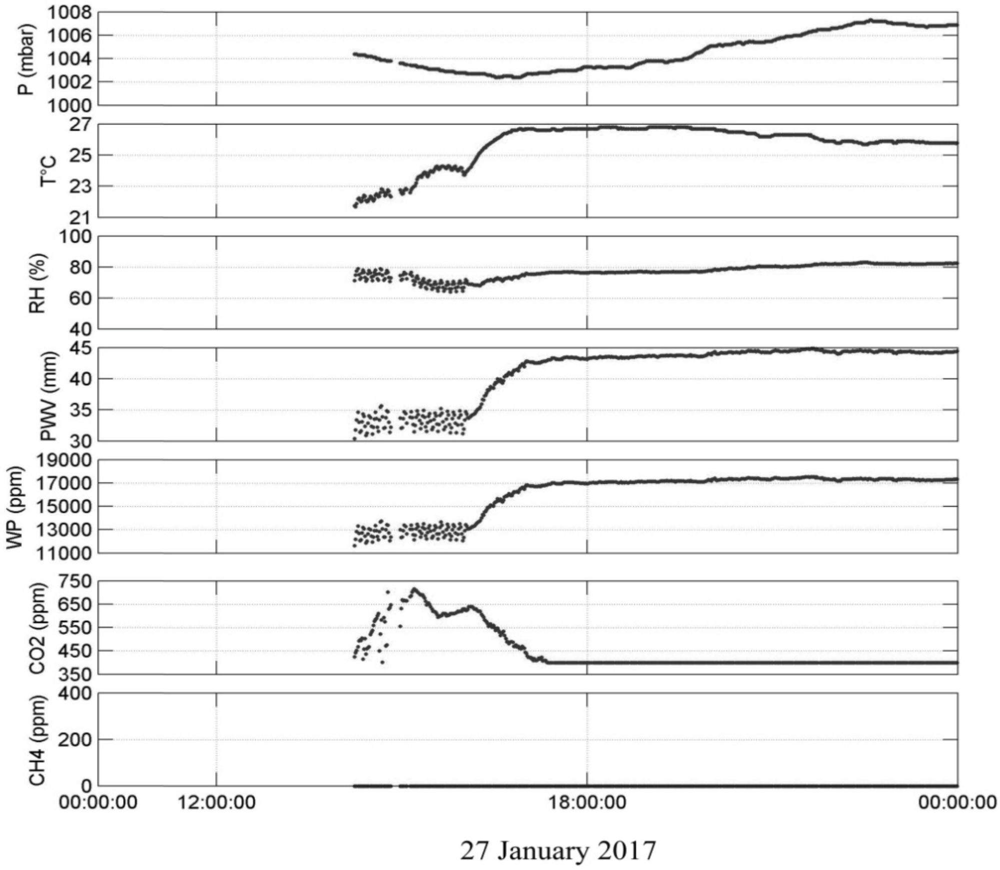

Fig. 8. The testing result of GHG monitoring system inside the laboratory for Jan 27, 2017.

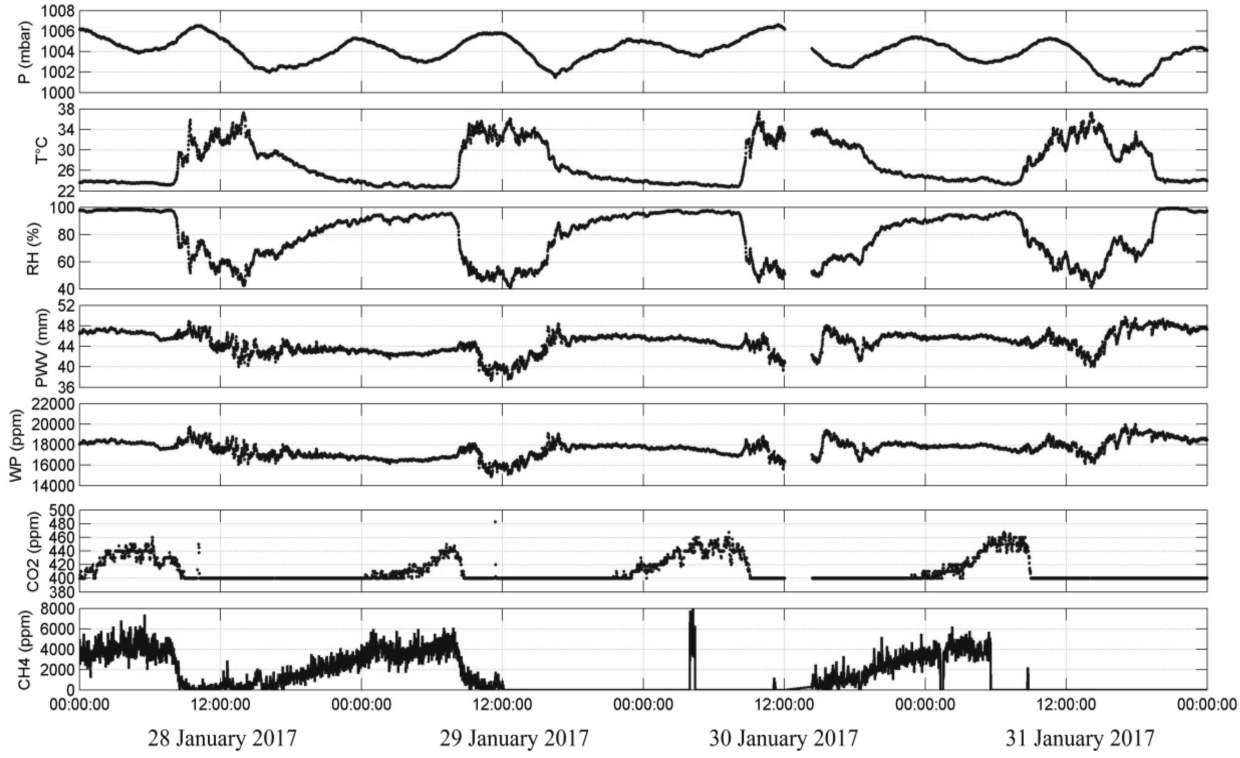

Fig. 9. The testing result of GHG monitoring system in outside the laboratory.

5. Conclusion

This study has succeeded in developing a smart GHG monitoring system deployed for peatlands consisting of integration hardware and Apps. The system was developed with several modules to enhance their performance such as RTC, watchdog, serial communication, and multiple UART channels. This Apps monitoring feature was built using OOP-based C# consisting of seven main threads and two additional threads. The OOP methods have been applied to reduce the complexity in Apps development. The advantages of the developed smart monitoring system are (1) capable to measure the surface meteorology, monitoring, and computation of GHG, storing the data to a micro SD as well as sending to web servers (Google Form and Dropbox) via a 3G connection; (2) capable directly compute PWV and WP values and can compare their patterns; (3) accurate time during measurement and has self-recovery if the Apps is reset; and (4) capable to create files, folders, and handle errors themselves automatically during the recording process. For future work, the system needs to be integrated with 5G connected Apps and websites that aim to provide long-term data, create awareness management, and conduct scientific studies to improve the accuracy of GHG forecasts.

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