IoT enabled Environmental Monitoring System

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Abstract. Nowadays, global warming poses a serious threat to our planet. For this reason, the reduction of the gas emitted into the atmosphere is increasingly sought for its purpose. Wireless Sensor Network (WSN) to monitor the concentration of carbon dioxide can therefore be helpful in monitoring air quality. In this research, the integration of wireless sensor networks into IoT is implemented for environmental monitoring. Subsequently, a practical case is described consisting in the implementation of a driver for reading the value of the environmental CO_2 concentration, through a sensor with NDIR technology. This paper presents a customized design of an IoT enabled environment monitoring system to monitor CO_2 concentrations. Moreover, the performance of low-cost Non-Dispersive Infra-Red (NDIR) was assessed. Thereafter, data related to the operation of the sensor will be graphically reported, as well as a sampling window that is executed to perform the measurement. Finally, possible future developments of the driver will be presented.

Keywords: Sensor, environment, monitoring, internet of things, CO_2

1 Introduction

The Internet of Things has the potential to change the world, just as it was for the Internet. Perhaps even more. It may seem like a risky statement, but think of the impact that the Internet has had on our society. Consider now that the Internet of Things, later referred to as IoT, is the natural evolution of the Internet which entails considerable improvement in collecting, analyzing and distributing data and information about the environment around us. IoT is a system whereby interrelated devices can exchange data over the Internet without requiring human-to-human or human-to-computer interaction [1]. In 2015, the world's population was about 7.35 billion people [2] and there were 15.41 billion Internet-connected devices [3]. With the current trend of development, in 2015 the connected devices are expected to be 25 billion, while in 2020 over 50 billion.

One application of IoT for better life is example environmental monitoring system. There is a close relationship between quality of life and the environment. Environmental quality is a key factor in people's well-being because quality of life is strongly affected by the health of the physical environment. Indicators of environmental quality encompass a number of environmental mediums, such as soil, water and air. The important indicator of air quality is related to CO_2 emissions.

In this paper, a new method of environment monitoring system based on a WSN technology is proposed. The system integrates wireless sensor nodes, advanced embedded gateways, and an IoT server. The proposed system stores and posts live data on the server. Additionally, it includes data backup tool at the sensor nodes and gateway levels, ensuring no data loss in the case of loss of communication within the system. The main contributions of this paper are as follows: (1) The designed IoT system enables the communication among different smart devices, including smart phones, microcontroller, and sensors. 2) The system provides solution for environmental monitoring system by using cutting edge technology.

The remaining part of this paper is organized as follows. Section 2 presents the background and the related work. Sections 3 presents the design of the IoT system and 4 present the testing of the proposed system. Finally, the conclusions are drawn in Section 5

2 Literature Review

In this section, the previous work of Internet of Things (IoT) and CO_2 sensor are presented.

2.1 Internet of Things

The Internet of Things (IoT) bring great value to our lives and societies by connecting all the things in our world. There are a number of applications of IoT implementation, for example smart home system.

IoT will provide solutions for Home Automation with which we will be able to remotely control our appliances as our needs. Proper monitoring of utility meters, energy and water supply will help saving resources [4]. Smart home technology provides homeowners security, comfort, convenience and energy efficiency by allowing them to control smart devices.

Moreover, researchers have conducted a number of efforts to investigate how IoT could build smart environments. In the smart environments, there are several features like: (1) remote control of devices, like power line communication systems to control devices, (2) device communication, using middleware, and wireless communication to form a picture of connected environments, and (3) information acquisition or dissemination from sensor networks. Santoso et al [5] presented a smart pH controller to monitor the acidity of environment. pH stands for the power of hydrogen. The numerical value of pH is determined by the molar concentration of hydrogen ions ($H+$). The lower the number, the more acidic the water is. The higher the number, the more basic it is. A pH of 7 is considered neutral. In this research, Android-based mobile phone is used to interact with sensors, microcontroller, and other tools through the internet wherever the user is.

A network for indoor and outdoor air quality monitoring is implemented [6] Each node is installed in a different room and includes tin dioxide sensor arrays connected to an acquisition and control system. In this research, advanced processing based on multiple-input-single-output neural networks is implemented at the network sensing nodes to obtain temperature and humidity compensated gas concentration values.

Lambebo and Haghani [7] implemented a real time environmental monitoring system using wireless sensor networks, capable of measuring temperature and greenhouse gas concentration levels including CO, CO_2 and CH_4 levels. A ZigBee wireless communication module based on IEEE 802.15.4 is used as the wireless communication unit in the sensor nodes. In this research, the security of data using encryption algorithm has not been addressed. In addition, the communication between the transmitter and the base station is crucial to collect the data without any interruption.

Brienza et al. [8] presented uSense, a low-cost cooperative monitoring tool that allows a real-time monitoring of the concentration of polluting gases in various areas of a city. In addition, they can share the collected data following a social networking approach. The sensor nodes used in uSense are Libelium Waspmote. They are equipped with an 8-bit microcontroller, and a WiFi module that allows TCP/IP and UDP/IP socket connections and HTTP/HTTPS communications. Each sensor node is provided with a gas sensor board, where CO, NO_2, O_3, temperature and humidity sensors have been mounted. This system is very interesting since sensor node can work even when the network connectivity is intermittent, so as to avoid data loss. In this case, in fact, the node can temporarily store the collected data in a SD card, waiting for the connection to be available again. However, the system does not provide improvement in sensor accuracy. The data quality provided by uSense depends on the accuracy of low-cost sensors. As the technology evolves, more accurate low-cost sensors will be made available and the data quality will improve accordingly.

A system to monitor the ambient air quality at indoor applications which using carbon dioxide detectors to combine mobile devices and networks is implemented. [9] Users can get information by using a mobile phone or computer to read quick response (QR) code or mobile communication confirm whether the places are safe and comfortable environments.

Polluino, a system for monitoring the air pollution via Arduino is implemented. [10] Moreover, a Cloud-based platform that manages data coming from air quality sensors is developed. The communication between sensors are using wire, it could limit the mobility of a system by the length of wires.

In this research, the use of wireless sensor networks for environmental monitoring is proposed. The proposed system uses sensors with NDIR technology to read the value of the environmental CO2 concentration.

2.2 CO_2 Sensor

Currently, with regard to the measurement of CO_2 concentration, there are several technologies exploited by the sensors: one based on the infrared absorption, while the others are based on electrolyte sensors. An example of this last type is the Severinghaus potentiometers sensor. They consist essentially of a glass electrode filled with an aqueous bicarbonate solution and covered by a membrane permeable to gas but not to water. The measurement of the concentration of carbon dioxide occurs by evaluating the pH of the aqueous solution, as CO_2, in water, forms carbonic acid, H_2CO_3, according to the reaction to equilibrium CO_2 (aq) + H_2O (l) *) H_2CO_3 (aq) [11] and therefore the pH is directly proportional to the concentration of the gas. This type of sensors has high maintenance costs, based on an indirect measurement. Moreover, the pH of the solution can also vary due to the presence of other gases [12].

Another method for measuring concentration is mass spectrometry, where, through a magnetic field, it is possible to separate the molecules of a sample [13]. This method is effective and highly expensive. Moreover, it is not yet able to make a small-sized apparatus. Another method is chromatography, which is much less expensive than mass spectrometry, but has much longer time to perform the analysis, but, as with the previous method, there is still no system available in small size. These are the reasons why in our days most sensors on the market exploit the infrared absorption technology, especially the Non-Dispersive InfraRed technology (NDIR) [14]. The operating principle of these sensors is based on spectroscopy, in particular, on the characteristic energy absorption of CO_2 in the infrared zone. It is known that each element has characteristic absorption spectra, determined by the energy levels typical of each molecule. The quantization of energy according to quantum theory and the equation that represents the energy of a photon, emitted or absorbed, as a function of its wavelength ν, $E = h\nu$ (where $h = 6.62606957 \times 10^{-34}\ m^2 \cdot kg/s$) [15].

The structure of an NDIR sensor is particularly simple. The infrared light, necessary for spectroscopy, is generated by a monochromatic emitter and is conveyed into two identical tubes. One is referred to as a reference, and is filled with gas which has no absorption in the infrared, for example nitrogen (N_2). The second tube contains the gas to be analyzed, and in particular absorbs more or less of the infrared radiation depending on the concentration of the gas. Thus, a detector compares the energy of the beam from both tubes. The difference is proportional to the amount of gas [12, 14]. The commercial NDIR sensors have the various pins, both an access to the detector relative to the reference tube, and to the active one. In this research, a microcontroller driver is written to evaluate the signals of the mentioned pins and calculate the gas concentration. It is good to note how the measurement is relative and determined by a difference of energies, therefore not absolute. This necessarily implies a process of calibration. Compared to the previous mentioned sensors and methods, the advantages of NDIR technology are lower cost, smaller dimensions, reduced response times, the possibility of continuously measuring and ultimately lower energy expenditure [16]. These are the main reasons why NDIR technology sensors are preferable for those applications that require a real-time measurement of CO_2 concentration with the additional constraint of low energy consumption.

3 Design and Implementation

The development of the driver for reading the value of the environmental concentration of CO2 will be described. These processes require above all a preliminary study phase, of a purely technical nature, characterized by an understanding of the functioning of the software development environment, the consultation of the sensor application notes and the study of the relative board on which it is mounted.

Programming the microcontroller of the board requires the installation of a tool chain in a Linux environment, which collects the tools needed to compile the driver and to flash the microprocessor. In this research, C++ programming language is used.

To perform the reading of the concentration of environmental CO2, literature study is needed. From the sensor datasheet, eight pins are counted, three of which are particularly relevant for reading the concentration. These are, in particular, pins 1, 4, 5, respectively: Lamp Return which drives the infrared emitter; Detector Output (ACT); Reference Output (REF). Lamp Return is a pin needed to power the infrared sensor emitter. It is controlled by an NMOS transistor and generated by the microcontroller. The measurement of the gas concentration essentially requires the knowledge of the amplitude of the two sinusoidal signals coming out of the ACT and REF pins as well as carrying out a calculation particularly laborious and heavy for the microcontroller: in particular, power elevations and logarithms. The measurement of the percentage of CO_2 in the air is a function of the ratio of these two quantities. Let us now give a brief description of the mathematical steps to be taken to arrive at the useful result of the concentration. First, an ABS quantity is defined, which indicates the absorption of infrared radiation in the sensor, as follows:

$$\boxed{ABS = 1 - \frac{I}{I_0}}$$

Where, I is the ratio between the two quantities ACT and REF, while I_0 is the ratio between them performed during calibration. The report giving the percentage concentration of CO_2 value is now given:

$$x = \left[-\frac{\ln(1 - \frac{ABS}{SPAN})}{b} \right]^{\frac{1}{c}}$$

SPAN is another parameter that can be calculated during calibration, while *b* and *c* are two parameters that can be extrapolated through regression on Absorbance. Non-linear effects and variations of the measurement due to the temperature that may occur, typical for this kind of sensors, are not taken into consideration.

The sensor requires an adaptation circuit, in particular of a band pass filter between 2 and 3 Hz, which includes the frequency of the signal used to drive the emitter.

A class `co2_t` was created, which makes the methods for reading and power management available. The class `co2_t` uses an auxiliary class created, named `measure_queue` that takes care of storing the data relating to sampling, in particular, implementing a static array that is filled cyclically. It also makes available the methods to inspect such data, such as the search for maximum and minimum value in the array. These allow to complete the collection of useful data for the measurement of the CO_2 value. When writing the driver, an alternative method for determining the maximum and minimum value of the amplitude of the two ACT and

REF signals are also considered. The implementation of a software trigger is a valid solution, moreover, results to be much less expensive from the point of view of occupying the memory with respect to that adopted by us. However, the presence of disturbances linked to the measurement has been found, which in fact make the determination of the rising and falling front of the two signals particularly complex. The solution to this problem would be the implementation of a Autoregressive Moving Average model (ARMA). Although if there are not particular problems of realization, the solution has been rejected because it is excessively complex and computational.

```
class co2_t: private power_manageable_if_t{
private:
   power_manager_t pwrmgr;
   power_manager_t *externalpwemgr;
   adc_channel_if_t *adc_ch_act;
   adc_channel_if_t *adc_ch_ref;
   gpio_if_t *lamp;
   timer_alarm_t alarm_measure;
   timer_alarm_t alarm_lamp;
   measure_queue measures;
private:
   virtual void on();
   virtual void off();
public:
   co2_t(power_manager_t *pwmcontroller);
   void init(adc_channel_if_t *adc_ch_act,
       adc_channel_if_t *adc_ch_ref,
       adc_channel_if_t *adc_ch_th, gpio_if_t *enable);
   measure read();
   static void lamp_task(timer_alarm_t* alarm); static
   void measure_task(timer_alarm_t* alarm);
};
```

Following is the file header of the `measure_queue` class. A measure structure has been created that contains both the data related to the ACT and the REF signals. The measure queue class is responsible for creating an array of measure values that contains all sample data. This array is filled cyclically, effectively overwriting any saved entries. It is for this reason that the array must have a sufficiently large size, it must contain enough samples to represent a period of the ACT/REF signal. The size of the array can be arbitrary and is chosen when creating the measure-queue object through the constructor to which the length parameter is passed. Within the class co2_t the `enqueue` method (uint16_t act, uint16_t ref) is mainly used to save the measured values, and the `getmeasure()` method that provides a measure value containing the amplitude of the ACT and REF signals, obtained through the `findmin()` and `findmax()` methods and a subsequent difference operation.

```
struct measure{
```

```
   uint16_t act;
   uint16_t ref;
};
class measure_queue{
   private: measure *measures;
   int length;
   int end;
private:
   int findmin();
   int findmax();
public:
   measure_queue();
   measure_queue(int length);
   void enqueue(uint16_t act, uint16_t ref);
   measure getmeasure();
};
```

4 Result and Discussion

The sampled data collection takes place through the cyclic filling of a static array. It follows an image of the data collected during a test of the operation of the driver. The search for the maximum and minimum value of both signals within the array completes the driver, since their difference makes the data I available.

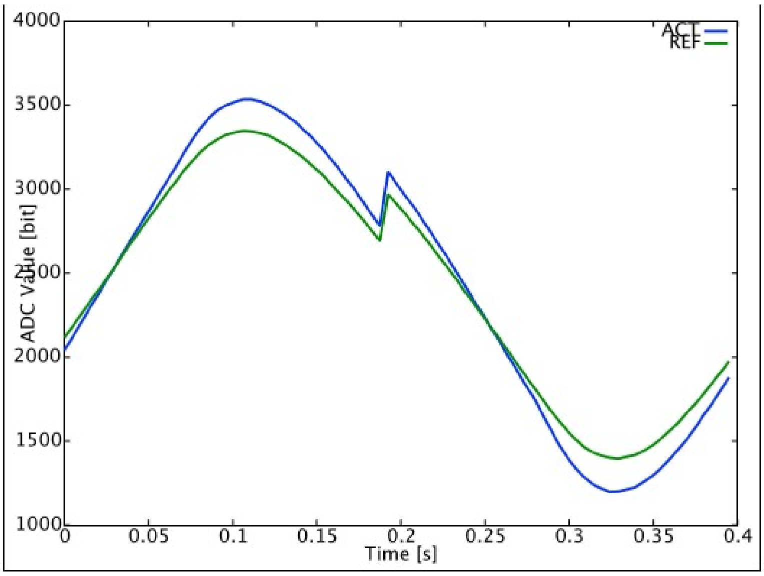

Fig. 1. Result of a sampling.

It can be seen from Fig. 1. how the amplitude of the two sin waves is different. It is also possible to observe the presence of a discontinuity due to the cyclic filling of the static array. The value in ordinate is read from the ADC measurement register, whose size is set to 12 bits, which implies a maximum value of 212 = 4096.

During some tests, saturation phenomena emerged at the output of the operational amplifier of the adaptation circuit. The modification of a resistance of the amplifier combined with an increase in the frequency of the signal useful to control the emitter (in this way the gain of the adaptation circuit, which has a rather narrow band pass characteristic, is modified), has been sufficient to solve the problem.

The NDIR CO_2 sensor is sensitive to temperature variations. In particular, the function x introduced in equation (3.2) will be a function of temperature. Thus, the concentration x will be denoted later as xT to highlight this dependency. The latter is modeled by modifying the equation (3.1) as follows:

$$x = \left(1 - \frac{I}{I_0}\right).(1 + \alpha.(T - T_{cal}))$$

The effect was studied through an octave script where we assumed Tcal = 25°C and $\alpha = 0.0007$. It has emerged that for the sensor used, operating in a CO_2 concentration range from 0% to 5%, the temperature effect is not so marked. Consequently, the compensation of effects related to temperature, which can be performed by measuring the temperature of the sensor by evaluating the output TH of the same, has not been implemented. The graph of xT (I / I_0) is shown below, resulting from the study of the phenomenon through simulation with octaves. From the graph of the xT (I / I_0) function, the following behavior is highlighted, as the CO_2 concentration increases, the ratio I = ACT/REF must decrease (I_0 is indeed a positive constant determined in calibration phase). Further confirmation regarding the slight variation in the measurement, due to the variation in temperature, is visible in Fig. 3. Through another script, the xT function was simulated by varying the temperature and keeping the ABS absorber value constant for three values, 0.1, 0.3 and 0.4. In particular, the following behavior is highlighted. The percentage error increases with the increase in the concentration of the gas and is directly proportional to the temperature T. It can be noted that, at prohibitive operating temperatures, the percentage error remains bound to 10%.

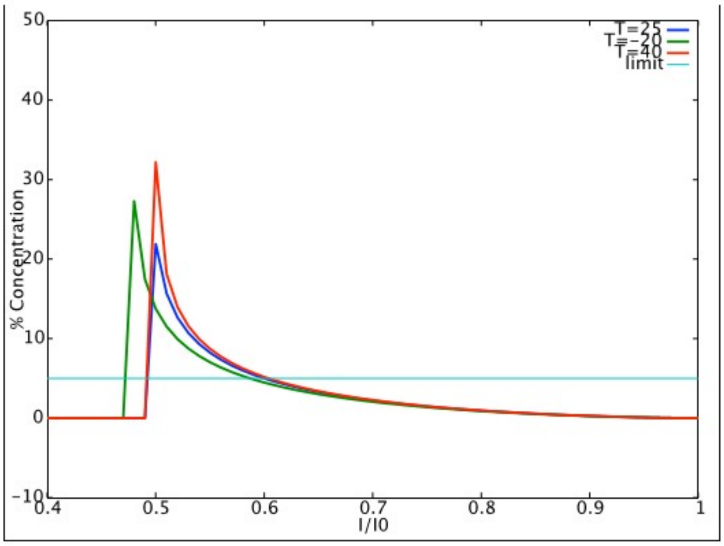

Fig. 2. CO_2% Concentration-ABS characteristic

To obtain a precise numerical result of the CO_2 concentration, an initial calibration phase would be needed, which goes beyond the scope of this work. This phase, which would be useful for determining parameters such as the reference value I0, would require a series of measurements in an environment with known gas concentration, through complex equipment not available for the activity of this thesis. However, we have been able to observe experimentally that the behavior described by the xT (I / I_0) function is respected.

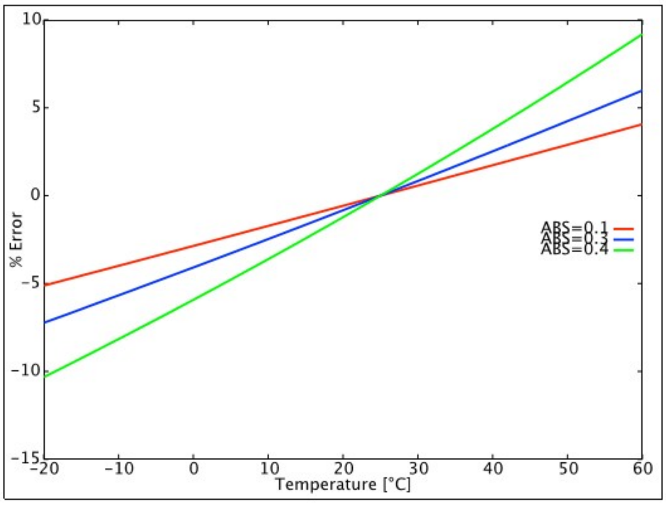

Fig. 3. Percentage error due to temperature variation for three ABS values.

5 Conclusions

The operation of the driver has been verified and the variations in the gas concentration are certainly detectable. The driver can be integrated into environmental parameter monitoring applications. A particularly simple application that does not require the knowledge of the precise value of the CO_2 concentration can be that of an alarm that indicates particularly high values of the gas. The natural environmental concentration of CO_2 is 0.03%; a value of 3%, for short periods of time, involves headaches, palpitation, increased respiration rate, while it can be fatal if exposure is prolonged beyond half an hour. After a first calibration to determine which is the ratio I/I_0 corresponding to this concentration, we can think of using the sensor with the driver made to signal this critical situation. A future development of the driver involves the calibration, useful to extrapolate the parameters.

A possible extension suitable for the purpose is the following. We can think of enabling the board's wireless connectivity, thus creating a REST-type web service that makes accessible the two significant measurement data, ACT and REF. A script present in the terminal that has access to the data will be able to complete the calculation to evaluate the gas concentration.

Extending the network on a large scale is also possible. It would thus be possible to gather useful information regarding any place in the city. This opens up to different possible applications. Consider, for example, an administration that wants to reduce city pollution. Through CO_2 mapping it could selectively limit the traffic flow of vehicles on roads with critical gas levels.

Moreover, an application for smartphone that relies on the aforementioned network can calculate a route with the lowest possible levels of CO_2 and guarantee a healthier run is very useful for outdoor activities.

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