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Artigo

Data Acquisiton and Transmission System for Carbon Dioxide Analysis

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Abstract

Despite being a minor part of the atmosphere's composition, the so-called greenhouse gases play a crucial role in their thermodynamics. Over the past 200 years, however, human activities have significantly altered the global carbon cycle. Thus, in the current context of global warming, quantifying, with increasingly reliable values, greenhouse gas emissions and the global carbon cycle has become one of scientists' priorities. This study aims to develop a system for acquisition and wireless transmission of carbon dioxide data from the C-Sense, a sensor manufactured by Turner Designs. As result, a reliable, compact and versatile circuit has been developed that acts as an embedded system for monitoring CO_2 concentration and partial pressure, as well as two temperature variables. Regarding the transmission of data via radio frequency, its data transmission has a range of 470 m without loss. A Python script has been implemented that stores data and generates real-time graphs for system monitoring.

Keywords: embedded system, concentration, C-sense, environmental monitoring.

Sistema de Aquisição e Transmissão de Dados para Análises de Dióxido de Carbono

Resumo

Apesar de constituírem parte minoritária na composição da atmosfera, os chamados os gases de efeito estufa desempenham um papel crucial em sua termodinâmica. Nos últimos 200 anos, entretanto, as atividades humanas alteraram significativamente o ciclo global do carbono. Desse modo, no atual contexto do aquecimento global, quantificar, com valores cada vez mais confiáveis, as emissões de gases do efeito estufa e o ciclo global de carbono tem se tornado uma das prioridades dos cientistas. Teve-se por objetivo com o presente estudo o desenvolvimento de um sistema de aquisição e transmissão sem fio de dados sobre dióxido de carbono, provenientes do sensor C-Sense, fabricado pela Turner Designs. Como resultado foi desenvolvido um circuito confiável, compacto e versátil, que funciona como um sistema embarcado para monitoramento de concentração e pressão parcial de CO_2, além de duas medidas de temperatura. Com relação à transmissão dos dados via radiofrequência, o mesmo possui alcance máximo de 470 m sem perda de dados. Foi implementado um script em Python que armazena os dados e gera gráficos em tempo real para monitoramento do sistema.

Palavras-chave: sistema embarcado, concentração, C-sense, monitoramento ambiental.

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1. Introduction

Carbon dioxide (CO_2) in the atmosphere plays a fundamental role in regulating the Earth's temperature through the greenhouse effect. However, in the past 200 years, human activities have significantly altered the global carbon cycle (Royer, 2006; IPCC, 2014). In the context of global warming, natural ecosystems play a key role in the annual carbon balance, as they exchange large amounts of CO_2 with the atmosphere and currently compensate for approximately 4 $PgCyr^{-1}$ of anthropogenic emissions. Transfers that occur between the surface of rivers and lakes with the atmosphere are an essential component for estimating the global carbon cycle. The lack of these CO_2 absorption measures that occur in inland waters compromises the estimate of the CO_2 balance of ecosystems (Raymond *et al.*, 2013). Thus, the development of data acquisition approaches, to quantify greenhouse gas emissions and the global carbon cycle with increasingly reliable values, has become one of the priorities of scientists in the area (Rasera, 2010; Raymond *et al.*, 2013).

In this context, sensor technology has gained popularity due to the need for recognition and identification of chemical, physical and biological systems, with gas sensors playing an important role in the detection of certain gases and monitoring of atmospheric changes (Das and Jayaraman, 2014). For the assessment of carbon dioxide, the two main current approaches are the use of electrochemical sensors or optical sensors (Mouman *et al.*, 2016). Electrochemical sensors have a lower cost, are relatively specific for singular and sensitive gases at ppm (parts per million) or ppb (parts per billion) levels, but generally have a short service life, and may also suffer from cross-response problems with other gases in the sample (Hodgkinson and Tatam, 2012).

Sensors based on optical absorption, however, are able to deliver faster responses with little interference from other gases in the measurements; can be used in real time and in situ; they have little deviation, considering their direct measurement method, and they have self-referenced measures (Hodgkinson and Tatam, 2012). Among the optical methods, sensors that perform analysis using infrared spectrometry (IR) are some of the most used. The spectral infrared regions are usually designed using non-dispersive infrared sensors (NDIR) having a bandpass filter to select the wavelength of the specific analyte absorption (Lobnik, 2008; McDonagh *et al.*, 2008; Liu *et al.*, 2012; Korotcenkov, 2013), in the case of CO_2, around 4.26 μm. However, such devices are limited by their cost, because of its size - which follows the path of light necessary for sufficient absorption to occur - and higher energy consumption (Moumen *et al.*, 2016.).

Recent advances in mobile communication technology, combined with the considerable reduction in the size of the sensors, made the use of wireless sensor networks in very diverse environments possible, which enables the implementation of weather stations and other data acquisition systems in various areas of environmental monitoring, without the need for constant human presence, so-called embedded systems (Garcia-Romeu *et al.*, 2012; Da Silva and Fruett, 2013).

Based on the aforementioned, the objective of this study is to develop a low cost system for the acquisition and wireless transmission of carbon dioxide data, using a CO_2 concentration and partial pressure sensor, based on a detector non-dispersive infrared (NDIR) with temperature compensation, having as main purpose, but not only, perform in situ environmental monitoring of these variables, being used as an embedded system or microstation, as well as assist in determining some of the variables necessary for calculating the carbon dioxide flux between water bodies and atmosphere.

2. Materials and Methods

The data acquisition system was designed to integrate the analog response of the carbon dioxide sensor, the responses of the temperature sensors, a Real Time Clock, a device for data storage and another device for data transmission (always seeking its redundancy), through a microcontroller. Figure 1 shows the proposed operational diagram.

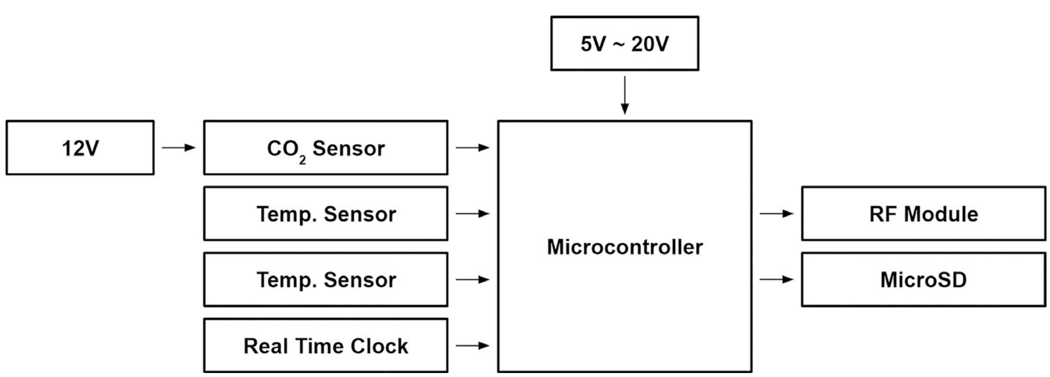

Figure 1 - System's operational block diagram.

2.1. Main components

2.1.1. CO_2 sensor

Quantities referring to CO_2 are generally expressed in different ways according to the environment where the measurements are made. To measurements taken in the air, concentration rates of carbon dioxide (xCO_2) are often reported in detriment of partial pressure (pCO_2). These units deal with fluctuations in CO_2 concentrations that are controlled by changes in ambient pressure and humidity, however, physical, chemical and biological processes are controlled by pCO_2 so, for certain applications, a conversion is necessary (Schar *et al.*, 2010).

Non-dispersive infrared (NDIR) sensors are widely used for direct measurements of CO2 in the atmosphere. For aquatic environments, some of the most widely used methods involve the use of headspace (Hope, 1995) and equilibrators (Frankignoulle *et al.*, 2001; Rasera 2010; Macklin *et al.*, 2018). However, with technology advancement, compact sensors, which can perform measurements continuously, began to be developed and used to determine pCO_2 values directly in situ (Reiman and Xu, 2018; Do Vale *et al.*, 2019; Yang *et al.*, 2019). Therefore, the sensor used in the system was the C-Sense (Fig. 2), a compact sensor, designed by Turner Designs, for measuring the concentration and partial pressure of CO_2 gas in fluids. The sensor uses a semipermeable, hydrophobic membrane in order to form an isolated headspace, where a non-dispersive infrared detector with temperature compensation performs the measurements. Thus, the equipment is capable of taking measurements in different types of fluids, with an operational range from 0 to 4000 ppm and ±3% of accuracy.

According to its manual, the operation of the C-Sense requires the supply of 6-12 V. For it to operate correctly, however, it is necessary to wait for a warm-up time from 45 s to 3 min. The sensor's analog output signal varies between 0 and 5 V and is proportional to the concentration of CO2 in the ambient, given by Eq. (1) (Turner Designs, 2019).

Figure 2 - C-Sense pCO_2 sensor.

$$CO_2 = (806,85 * V) - 42 \tag{1}$$

The sensor was chosen to the system since it has as an advantage, besides its small size, the fact that it does not requires the use of an equilibrator nor floating chambers, due to its hydrophobic membrane and isolated headspace, making it a good option for use in embedded systems measurement devices. In addition, the sensor proves to be quite versatile, since new calibrations can be made for different environments, being only necessary to determine a new conversion equation. If needed, it is possible to configure the sensor to measure the atmospheric CO_2 concentration of the altitude at which it is located and, subsequently, use it in conjunction with a total pressure sensor of the ambient to determine the partial pressure of CO_2. Do Vale *et al.* (2019) used the sensor in laboratory tests and found accurate measurements of pCO_2 in air and water. However, he suggested that for measurements for periods longer than 24 hours in certain environments, care should be taken with the formation of biofilm in the sensor membrane, which may affect its performance. In spot measurements and for shorter periods of time, such as those performed by Jun Xu *et al.* (2019) and Yang *et al.* (2019) the device has proven to be quite effective.

As shown in Fig. 3, despite the noise, the sensor is capable of measuring values in low time intervals and accurately describes the behavior of the environment it is located, due to a smoothing of the data curve in 6 min. In comparative tests carried out in the laboratory, where air was pumped through the detection chambers of the C-Sense and a previously calibrated Li-Cor® 820 CO_2 Analyzer, the sensors showed a 98.3% correlation in their behavior.

2.1.2. Temperature sensors

For the evaluation of certain procedures, one or more temperature measurements are necessary. Thus, considering a wider range of applications, two DS18B20 sensors, manufactured by Dallas Instruments®, were used. The sensors measure temperature using an onboard proprietary temperature measurement technique, counting the number of clock cycles of an oscillator with a low temperature coefficient. This low-cost sensor has the advantage of being digital, able to read the temperature, interpret it and send the data already converted to the microprocessor using a single wire bus, that is, two sensors or more can use a sole microcontroller port. The chosen sensor was encapsulated in a metallic container, in order to be able to measure temperature in dry, humid environments and even in water. Its accuracy is ± 0.5 °C, with an operating range of -55 to 125 °C (Maxim Integrated, 2018).

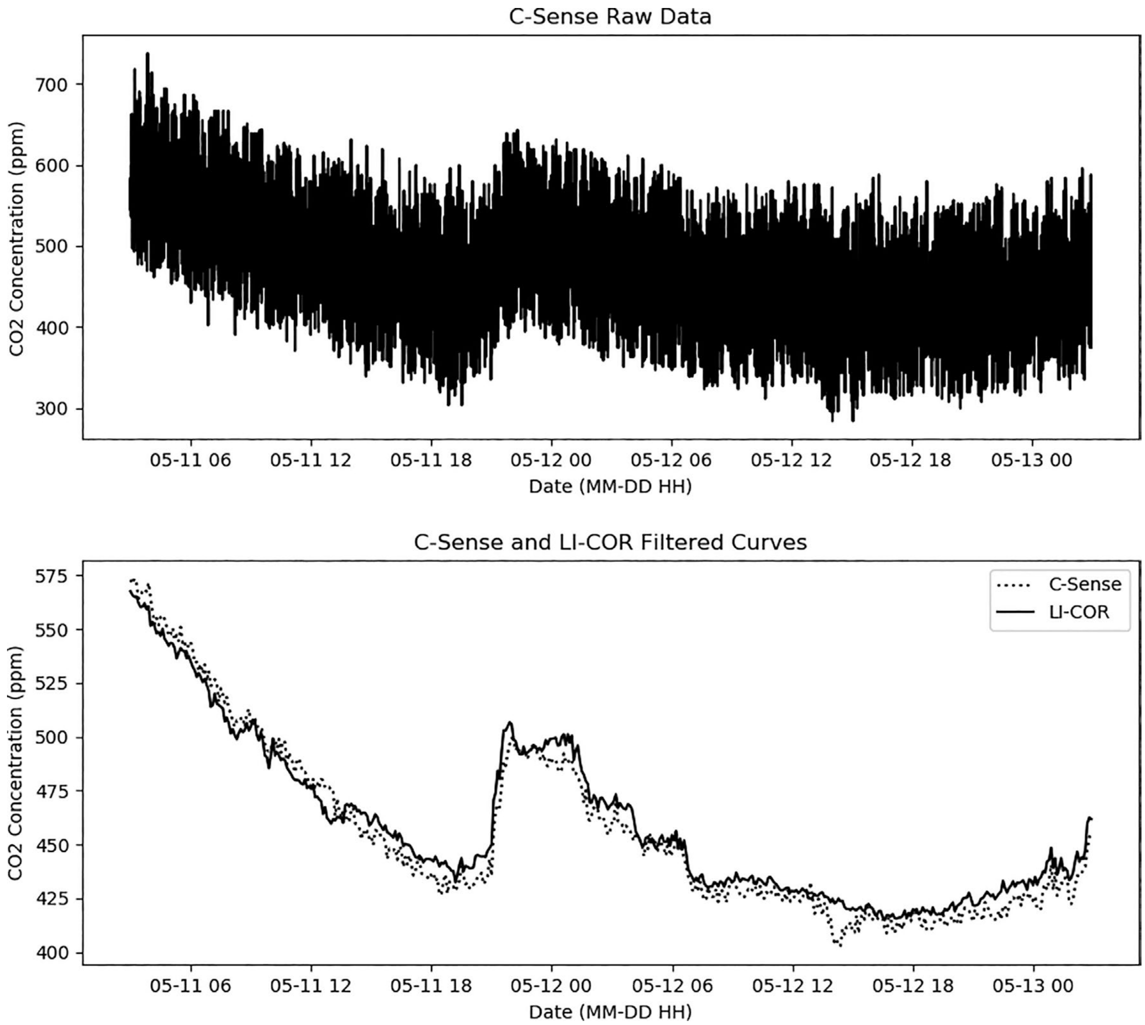

Figure 3 - C-Sense operation. Raw data curve with an acquisition frequency of 1 s and comparative measurements curve of the sensors C-Sense and Li-Cor 820, with 6 min smoothing.

2.1.3. Real time clock

The Real Time Clock (RTC) used in the system was the Sparkfun DS3234 Real Time Clock, although being a low cost peripheral that uses Serial Peripheral Interface (SPI) protocol, it is extremely accurate, due to an internal temperature compensation of the oscillating crystal mechanism, which makes possible to maintain an accuracy of ± 2 ppm (part per million), which corresponds to a variation lesser than 0.2 s per day, working at temperatures from 0 to 40 °C. This device also has a small 3 V CR1224 battery, so even without external power to the clock module, the battery cell can maintain the RTC time accurately for about 9 years (Maxim Integrated Products 2010; Ali *et al.*, 2016).

2.1.4. Microcontroller

To control the circuit processes, the Arduino Nano was chosen, for being a small, complete and easy to use board, based on the ATmega328P microcontroller. This model uses a Mini-B universal serial bus (USB) cable and can be powered via connecting cable or an external 6-20 V power supply. The Arduino Nano has 14 digital and 8 analog pins operating by default at 5 V. According to Arduino® (2020), digital pins can be used as a signal input or output through the functions pinMode(), digitalWrite(), and digitalRead(), providing or receiving a maximum of 40 mA. Analog pins, on the other hand, uses an analog-to-digital (A/D) converter providing 10 bits of resolution, that is, 1024 different values.

2.1.5. MicroSD transflash breakout

In order to increase the reliability of the assembled circuit was opted for redundancy in the storage of the obtained data. For this purpose, in addition to sending and storing it on another computer, a micros Transflash Breakout, a module that operates at 3.3 and 5 V voltages, and uses an SD/MMC socket, allowing the insertion of external memory cards, was also installed.

2.1.6. Radio frequency module

In the circuit project, two data storage options were chosen. One of them for sending and saving the measured values on another device. For this task, the XBee Pro S2B module, a card that communicates via radio frequency using the Zigbee standard, was chosen. According to Digi International (2018), this module has a range of up to 3.2 km transmitting at a speed of up to 250 kb/s.

In order for XBee to be able to send and receive data, it is necessary to configure it on a computer. However, the module is designed to be used directly on a circuit board, to do so, it must use an adapter to connect it to the USB port (Faludi, 2010). The adapter used during this work was the SparkFun XBee Explorer Dongle, one of the smallest and most versatile, since it does not require an external cable. The XBee radio has 20 connecting pins with 2 mm spacing between them, so it was necessary to use another adapter to fit it on the perforated plate. The adapter used was the SparkFun XBee Explorer Regulated.

Each XBee has an internal microcontroller that runs a program known as firmware, responsible for executing its addressing, communication and security process and utility functions. The XCTU software was used to configure the functions of the two XBee modules used in the job. One was set up as “coordinator”. This is the radio responsible for forming the network, distribute addresses and managing the other functions that define, protect and maintain it. The second radio was configured as “end device”, the simplest form of configuration, being able to connect to the network created by the first module and receive information. The coordinator was attached to the circuit, in order to collect and send data from the sensors, while the end device was connected to the computer, in order to receive this data. The choice of Zigbee communication is due to the possibility of creating a network of transmitters, significantly increasing the range of data transmission.

2.2. Scripts

The logical part of the data acquisition system was implemented using the Arduino development ambient, following the Structured Programming paradigm, where the code is divided into blocks and follows execution routines and loops. The first block consists in importing the necessary libraries for the communication of the devices with the microcontroller, followed by the instantiating of these libraries and stating the variables with their respective data types. The second part of the code is where the instances defined in the previous block are initialized and configured with initialization parameters. Finally, the third part is where the repetition loop occurs until the system is turned off, being responsible for updating the clock time, making the reading, storing the measured data on the SD card, sending them and, finally, saving them on the receiving device. The developed algorithm is presented and commented in supplementary material S1. Upon receiving the data on your computer, it is up to the user to record them. However, in order to facilitate the monitoring of the system, a Python script was developed, presented in supplementary material S2, for the automatic generation of graphics and storage of the received values.

3. Results and Discussion

Figure 4 shows the result for the system's manufacturing process, being portable and compact. The connectors for the temperature and carbon dioxide sensors are located around 10 cm from the perfboard, allowing for

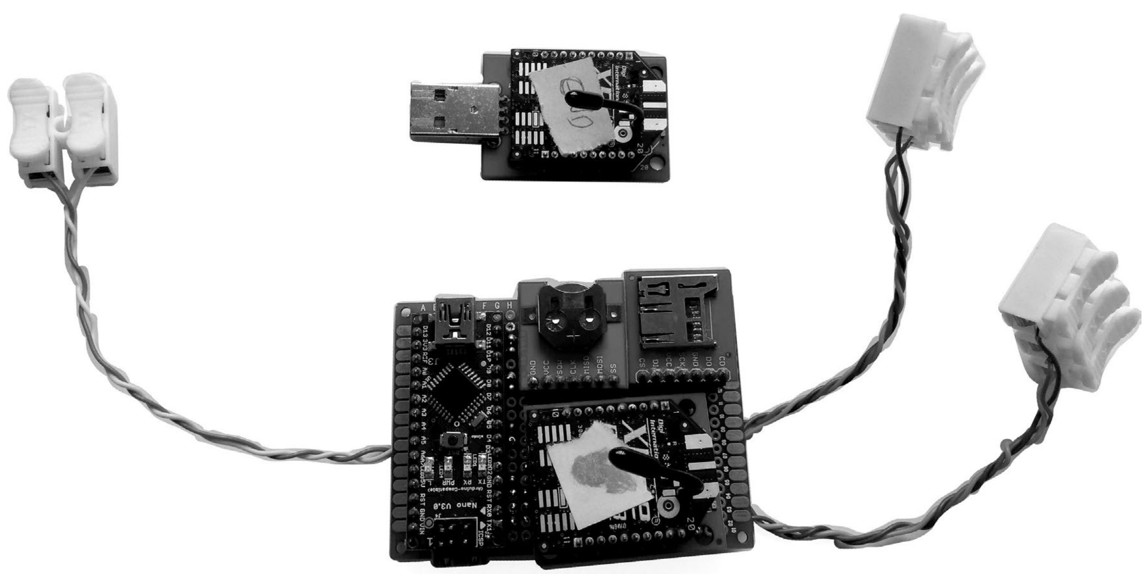

Figure 4 - System set in a perfboard, with three connectors to external sensors and in the top of image the radio frequency receiver.

easiness of handle of the circuit during experiments and data measurements. It was decided to use solderless or screwless connectors, in order to approach a plug and play concept. The circuit schematic draft is shown in Fig. 5 for future replication and improvements.

The circuit was designed to also function as an embedded system, passing through V-Model development phases and fulfilling the requirements presented by Marwedel (2018), in order to assist the monitoring of CO_2 flux on aquatic environments. Besides of being powered by a 5 V mini Universal Serial Bus cable (USB), the microcontroller can operate with a non-regulated external power supply from 6 to 20 V through a borne connector linked to pins 29 and 30, assuring autonomy in accordance with the chosen battery system.

The voltage regulator in the microcontroller assures that the peripherals to it attached, which operate with 3.3 or 5 V, will not get damaged. The C-Sense sensor operates with an external power supply, possessing only two wires, ground and analog signal with a 5 V output, connected to the circuit, the other devices are powered by the microcontroller, that performs the previously programmed tasks: data conversion, storage and transmission.

Regarding the storage and transmission of data via radio frequency, the algorithm purpose was to create a well-defined pattern, in order to facilitate future reading and analyses. As shown in Fig. 6 (a), each line follows a sequence where observed values are represented through peripherals attached to the circuit. Data output show date, time (GMT- 3), temperature of the sensors in Celsius (°C), analog signal read on the microcontroller pin, C-Sense signal responses and CO_2 concentration. The data is saved in comma-separated values format (.csv). Figure 6 (b) presents the temperature and CO_2 concentration graphics generated by the written script in python language, for the monitoring of the system and storage of acquired data.

System's response time, however, was unexpected. Keeping in mind the capacity of the CO_2 sensor to measure in higher frequencies, the delay chosen in the code used was of 1000 ms, that is, the system would save and/or show a measured value each second. The data, however, has shown a delay of around 500 ms. The cause of this slower answer is associated to the two digital temperature sensors, for, even if counter intuitive, once the digital data can be processed and transmitted in a more efficient way than analog data (Floyd, 2007), the sensors work with a connection system 1-Wire, similar to the concept of I^2C, but with low data transfer rate: 16.3 kb/s (Maxim Integrated, 2009). Another factor that points towards this hypothesis is that the response time rose whilst the two sensors were placed in different ports on the microcontroller, having in sight the opening of two communication ports at each repetition lace. When placed on a single pin, the delay fell by half. That delay, however, generates little influence to the environment analyses, for the abrupt

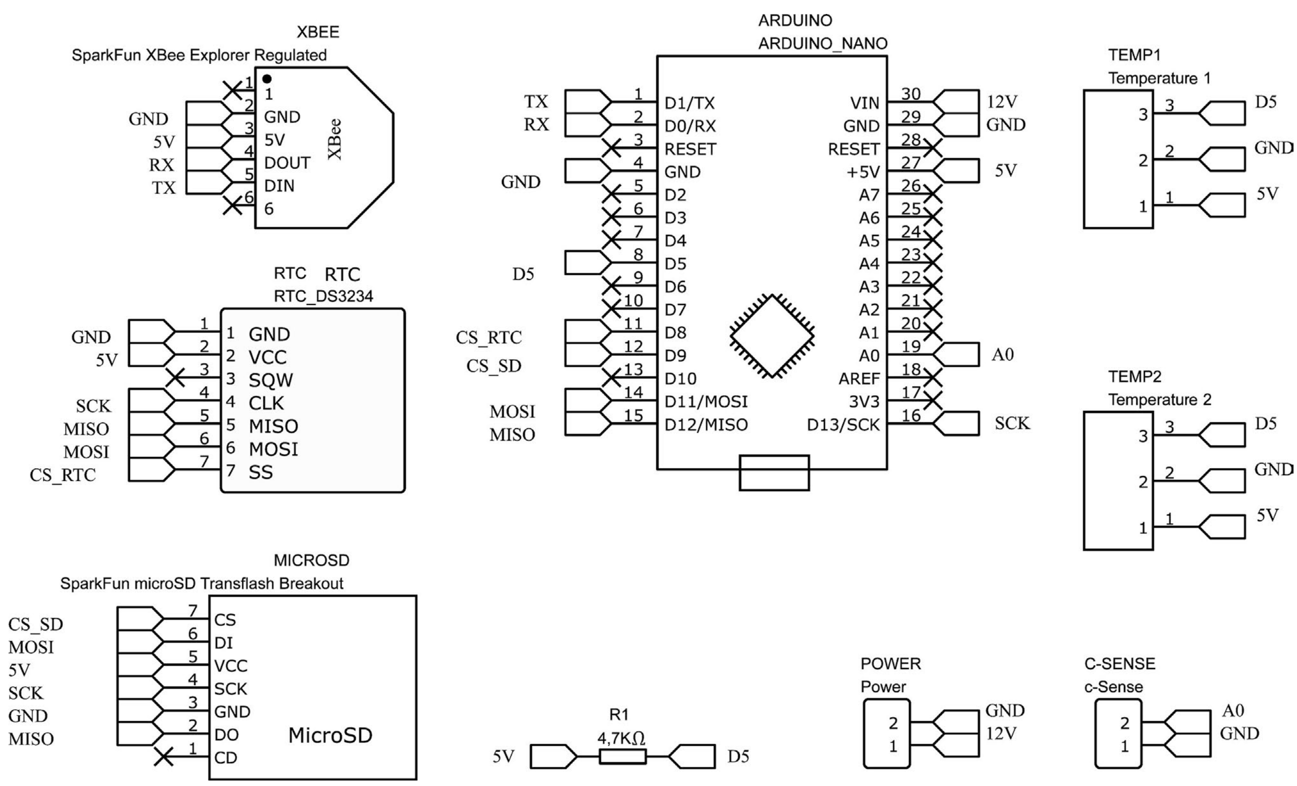

Figure 5 - Circuit schematic.

a)

```
date,     time,     temp1, temp2, analog, volts, co2
10/5/19, 19:28:56, 26.25, 26.44, 165.00, 0.81,  619.05
10/5/19, 19:28:59, 26.25, 26.44, 157.00, 0.77,  587.53
10/5/19, 19:29:1,  26.25, 26.44, 181.00, 0.88,  682.09
10/5/19, 19:29:4,  26.25, 26.44, 190.00, 0.93,  717.54
10/5/19, 19:29:6,  26.25, 26.25, 167.00, 0.82,  626.93
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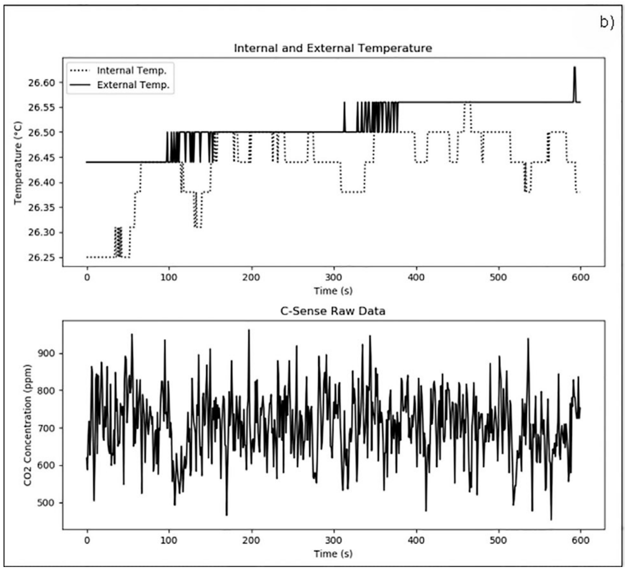

Figure 6 - Data output model. (a) Data saved on SD card. (b) Python script plot. At the top of the image, the plot of temperature values and, at the bottom, the CO_2 measurements. The temporal resolution of 600 s can be altered in the code.

variations of temperature in a period of time that short are diluted in the statistic treatment.

3.1. Functionality tests

Tests of range and functionality were performed, to evaluate the performance of the developed system, simulating its continuous operation in field. These tests goal was to determine the maximum reach range of data transmission and the sensors answer to environmental change. First was performed a functionality test. The circuit was assembled in a waterproof plastic box and left in the Atmospheric Physics and Chemistry Laboratory, on Tapajós Campus of the Federal University of Western Pará (UFOPA), at latitude 2°25'10" S and longitude 54°44'22" W, from 06:00 hours (GMT -3) of May 11th, 2019 until 06:00 hours (GMT -3) of May 13th, 2019, with the C-Sense being calibrated to measure the CO_2 concentration and the two temperature sensors collecting internal and external environment data of the laboratory. The results from these two days are shown in Fig. 7. By the end of the test, although the small delay to the temperature sensors, after measurements and statistical treatment, the behavior of the environment was represented as expected and the system did not present packet loss.

To settle the maximum range between the two modules of radio frequency, a test was performed with the system in an environment with an uneven ground and with

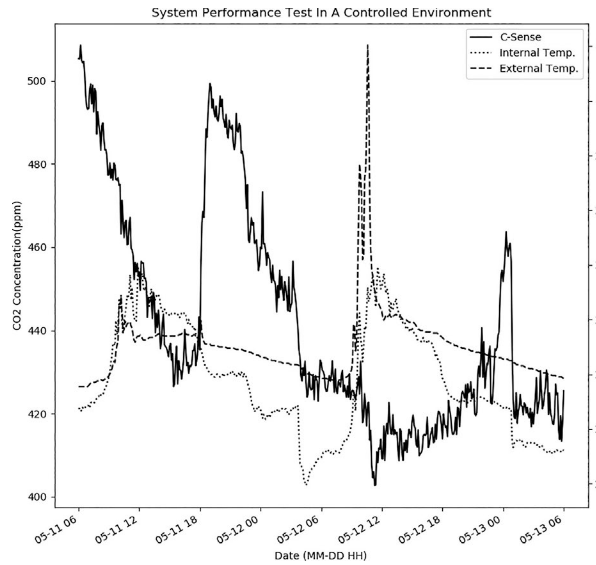

Figure 7 - System performance test in a controlled environment during two days. The solid line represents the variation in the concentration of atmospheric CO_2 in an open environment measured by C-Sense. The dashed lines represent the temperature variation inside and outside the laboratory where the tests were performed.

structures that might provoke interference in the signal strength. The test was performed in the city of Santarém – PA, where Tapajós Campus – UFOPA is located, with regular weather conditions and in constant linear movement. The system achieved a maximum reach, without compromising of data transfer, of approximated 470,6 m (Fig. 8). Worth mentioning that, in case of higher reach necessity, tests performed by Picanço *et al.* (2016), in the same site were this experiment was performed, indicate that a Xbee Pro 900HP module was capable of transmitting data, without package loss, at a distance of 839.64 m. The module substitution in the developed system does not

Figure 8 - System's maximum range test. Federal University of Western Pará is indicated. Image source: Google Earth.

require structural changes on the code lines, being necessary only the configuration of its firmware.

Some factors, however, must be taken into consideration before adopting this kind of methodology for measures of CO_2. The study area must be previously analyzed for two different reasons: (1) the operational range of the sensor and (2) the measurement approach. Due to a number of physical, chemical and biological process, quantities regarding the carbon dioxide vary spatial and temporally (Abril, *et al.*, 2014; Do Vale, *et al.*, 2019) and the developed system performs measurements in a single spot of the research area in a determined time interval. For very large sites, that can be bypassed using a sensors network, which collect data in multiple spots at the same time and may communicate through the ZigBee network. Other solutions can the pointed in the works of Podgrajsek *et al.* (2014), that when measuring pCO_2 in lake Tämnaren, in Sweden, used a correction factor of 200 ppm due to the its non-homogeneity; and Macklin *et al.* (2018), in order to achieve a larger spatial resolution of sampling in Indonesian lakes, has set up a measurement system in a small research boat driven between 4 and 6 km/h.

4. Conclusion

This study developed a low-cost system for the acquisition and transmission data related to CO_2. Thus, a C-Sense sensor and two DS18B20 digital temperature sensors were integrated into a circuit whose processes are controlled by an Arduino Nano microcontroller in order to measure, store and transmit data via radio frequency. The tests carried out shows that the system behaves in a safe and reliable way, being able to be used for spot measurements or as an embedded system for prolonged measurements. Its advantages are the fact that it is small, resistant and practical, being capable of sending data over a maximum distance of approximately 470,6 m without data package loss, being simple to modify it to increase performance and possible repairs. The C-Sense sensor proved to be a good option for measurements of this kind, in view of the plug and play concept in which it was designed, being able to perform direct and in situ measurements, eliminating the usage of large devices such as equilibrators or floating chambers, and it is also a less complex methodology than headspace measurement. In addition, the sensor can be calibrated for atmospheric and aquatic measurements, and showed a 98.3% correlation of its behavior in relation to the Li-Cor® 820 CO_2 Analyzer. As a result of the tests, despite the large amount of noise in their measurements, a 6-min smoothing of the data curve proved to be effective for a good representation of the studied environment. Finally, a python script that allows monitoring the data received by radio frequency was developed, plotting real-time graphs of the measured variables and automatically saving them to the device where the receiver is located.

References

ALI, S.A.; ZANZINGER, Z.; DEBOSE, D.; STEPHENS, B. A low-cost Arduino-based platform for long-term indoor environmental data collection. **Building and Environment**, v. 100, p. 114-126, 2016.

ABRIL, G.; BOUILLON, S.; DARCHAMBEAU, F.; TEODORU, C.R.; MARWICK, T.R.; TAMOOH, F.; OCHIENG OMENGO, F.; GEERAERT, N.; DEIRMENDJIAN, L.; POLSENAERE, P.; BORGES, A.V. Technical Note: Large overestimation of pCO2 calculated from Ph and alkalinity in acidic, organic-rich freshwaters. **Biogeosciences**, v. 12, p.n. 1, p. 67-78, 2015.

ARDUINO. **Linguagem Arduino: Manual de Instruções**. Ivrea: Arduino, 2019. Disponível em: https://www.arduino.cc/reference/pt/language/functions/analog-io/analogread/

DA SILVA, M. S; FRUETT, F. Monitoramento ambiental através de rede de sensores sem fio de baixo custo. In: **XVI Simpósio Brasileiro De Sensoriamento Remoto**, Foz do Iguaçu, p. 1908-1914, 2013.

DAS, S.; JAYARAMAN, V. SnO2: A comprehensive review on structures and gas sensors. **Progress in Materials Science**. v. 66, p. 112-255, 2014.

DIGI. **Zigbee RF Modules: XBEE2, XBEEPRO2, PRO S2B - Modules User Guide**. Hopkins: DIGI, 2018. Disponível em: digi.com/resources/documentation/digidocs/pdfs/90000976.pdf.

DO VALE, R.S.; DE SANTANA, R.A.S.; DA SILVA, J.T.; SILVA, R.; DOS SANTOS, M.R.P.; DE ANDRADE, A.M.D. Comparison of headspace and compact sensor measurements of tropical lakepCO_2. **IOSR Journals**, v. 13, n. 3, p. 8-14, 2019.

FALUDI, R. **Building Wireless Sensor Networks**. 1. ed. Gravenstein: O'Reilly Media, 321p., 2010.

FLOYD, T.L. **Sistemas Digitais: Fundamentos e Aplicações**. 9. ed. Porto Alegre: Bookman, 888 p., 2007.

FRANKIGNOULLE, M.; BORGES, A.; BIONDO, R.; A new design of equilibrator to monitor carbon dioxide in highly dynamic and turbid environments. **Water Research**, v. 35, n. 5, p. 1344-1347, 2001.

GARCIA-ROMEO, D.; FUENTES, H.; MEDRANO, N.; CALVO, B.; MARTINEZ, P.A.; AZCONA, C. A NDIR-based CO2 monitor system for wireless sensor networks. In: **3rd Latin American Symposium on Circuits and Systems**, Playa del Carmen, p. 1-4. 2012.

HODGKINSON, J.; TATAM, R. P.; Optical gas sensing: a review. **Measurement Science and Technology**, v. 24, n. 1, 2012.

HOPE, D.; DAWSON, J.J.C.; MALCOM, S.C.; BILLET, M.F. A method for measuring free CO2 in upland streamwater using headspace analysis. **Journal of Hydrology**, v. 16, n. 1-2, p. 1-14, 1995.

INTERGOVERMMENTAL PANEL ON CLIMATE CHANGE. **Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Inter-**

governmental Panel on Climate Change. Geneva: IPCC, 151 p., 2014.

JUN XU, Y.; XU, Z.; YANG, R. Rapid daily change in surface water pCO2 and CO2 evasion: A case study in a subtropical eutrophic lake in Southern USA. **Journal of Hydrology**, v. 570, p. 486-494, 2019.

KOROTCENKOV, G. **Handbook Of Gas Sensor Materials: Properties, Advantages And Shortcomings For Applications Volume 1: Conventional Approaches**. New York: Springer, 454 p., 2013.

LIU, X.; CHENG, S.; LIU, H.; HU, S.; ZHANG, D.; NING, H. A survey on gas sensing technology. **Sensors**, v. 12, p. 9935-9665, 2012.

LOBNIK, A. Absorption-based sensors. In: BALDINI, F.; CHESTER, A.N.; HOMOLA J.; MARTELLUCCI, S. **Optical Chemical Sensors**. Dordrecht: Springer, v. 224, p. 77-98, 2006.

MACKLIN, P.A.; SURYAPUTRA, I.G.N.A.; MAHER, D.T.; SANTOS, I.R. Carbon dioxide dynamics in a lake and a reservoir on a tropical island (Bali, Indonesia). **Plos One**, v. 13, n. 6, p. 1-20, 2018.

MARWEDEL, P. **Embedded System Design**. Amsterdan: Springer, 423 p., 2018.

MCDONAGH, C.; BURKE, C.S.; MACCRAITH, B.D. Optical chemical sensors. **Chemical Reviews**. v. 108, n.2, p. 400-422, 2008.

MAXIM INTEGRATED PRODUCTS. **Extremely Accurate SPI Bus RTC with Integrated Crystal and SRAM: Data Sheet**. San Jose: Maxim Integrated Products, 2010. Disponível em: https://datasheets.maximintegrated.com/en/ds/DS3234.pdf.

MAXIM INTEGRATED. **Programmable Resolution 1-Wire Digital Thermometer: Data Sheet**. San Jose: Maxim Integrated Products, 2018. Disponível em: https://datasheets.maximintegrated.com/en/ds/DS18B20.pdf

MAXIM INTEGRATED. **Reading and Writing 1-Wire® Devices Through Serial Interfaces: Application Note 74**. San Jose: Maxim Integrated Products, 2009. Disponível em https://www.maximintegrated.com/en/design/technical-documents/app-notes/7/74.html.

MOUMEN, S.; RAIBLE, I.; KRAUß, A.; WÖLLESTEIN, J. Infrared investigation of CO2 sorption by amine based materials for the development of a NDIR CO2 sensor. **Sensors and Actuators B: Chemical**, v. 236, p. 1083-1090, 2016.

PICANÇO, G.A.S.; DA SILVA, J.T.; DE SANTANA, R.A.S.; DO VALE, R. Desenvolvimento de uma sonda atmosférica sem fio para estudos ambientais de baixo custo. **Ciência e Natura**, v. 38, n. 1, p. 118-121, 2016.

PODGRAJEK, E.; SAHLÉE, E.; BASTVIKEN, D.; HOLST, J.; LINDROTH, A.; RUTGERSSON, A. Comparison of floating chamber and eddy covariance measurements of lake greenhouse gas fluxes. **Biogeosciences**, v. 11, p. 4225-4233, 2014.

RASERA, M.F.F.L. **Determinação Dos Fluxos De CO_2 E Parâmetros Físicos Envolvidos Neste Processo Em Diferentes Ambientes Fluviais Da Amazônia**. Tese de Doutorado, Piracicaba, 2010.

RAYMOND, P. A.; HARTMANN, J.; LAUERWALD, R.; SOBEK, S.; MCDONALD, C; HOOVER, M.; BUTMAN, D.; STRIEGL, R.; MAYORGA, E.; HUMBORG, C.; PIRKKO, K.; DURR, H.; MEYBECK, M.; CIAIS, P.; GUTH, P. Global carbon dioxide emissions from inland waters. **Nature**, v. 503, p. 355-359, 2013.

REIMAN, J.H.; JUN XU, H. Diel variability of pCO2 and CO2 outgassing from the lower Mississippi River: Implications for riverine CO2 outgassing estimation. **Water**, v. 11, n. 43, p. 1-15, 2019.

ROYER, D.L. CO_2-forced climate thresholds during the Phanerozoic. **Geochimica**, v. 70, n. 23, p. 5665-5675, 2006.

SCHAR, D.; ATKINSON, M.; JOHENGEN, A.; PINCHUK, H.; PURCELL, C; ROBERTSON,; G.J.SMITH; TAMBURRI, M. **Performance Demonstration Statement Pro-Oceanus Systems Inc. Psi Co2-Protm**. Maryland: Alliance for Coastal Technologies, 2010.

SEITZ, J.; TONG, C. **LMP91051 NDIR CO_2 Gas Detection System: Application Report**. Dallas: Texas Instrument Incorporated, 2013. Disponível em: ti.com.cn/cn/lit/an/snaa207/snaa207.pdf.

TURNER DESIGNES. **C-sense in situ pCO2 Sensor: User's Manual**. San Jose: Turner Designes, 2019. Disponível em: https://www.turnerdesigns.com/c-sense-in-situ-pco2-sensor.

YANG, R.; XU, Z.; LIU, S.; XU, Y.J. Daily pCO_2 and CO_2 flux variations in a subtropical mesotrophics hallow lake. **Water Research**, v. 153, p. 29-38, 2019.

Supplementary Material

SM 1 - Algorithm used by Arduino for data processing.

SM 2 - Python language algorithm for data storage and automatic plotting of measured values.