Initial Prototype of Low-Cost Stool Monitoring System for Early Detection of Diseases

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Abstract. Even though cancer is one of the most common diseases in the 21st century, early detection tests are still expensive and invasive. In this work, a initial stool monitoring prototype for the early detection of this disease is proposed. The emerging and growing concept of Internet of Things has been considered for the implementation of this prototype. So, MOX (Metal OXide, metal-oxide-semiconductor type) sensors to detect volatile organic compounds (VOCs) and a thermal camera are integrated into different development boards, which send the collected data of stool to monitoring it by means of an IoT platform. With the result of this initial prototype, a proof of concept has been obtained for testing with cancer experts.

Keywords: Stool monitoring system · Volatile organic compounds (VOCs) · MOX sensors · Thermal camera · Internet of Things

1 Introduction

Colorectal cancer (CRC) is the third most common tumour worldwide (1.93 million cases) and was the second most common cause of death in 2020 (935,000 deaths). Early detection and early treatment have been shown to reduce cancer mortality. To achieve this, population-based screening is carried out to identify people who may have the disease on the basis of age and risk factors. Some of these risk factors include unhealthy diet, smoking, physical inactivity and obesity [24].

However, the most common screening tests currently available for CRC pose significant disadvantages, as they are invasive, painful, costly for the healthcare system and, in some cases, require patient preparation and sedation [23,25].

Scientific evidence has shown the power of canine olfactory systems to detect volatile organic compounds (VOCs), which differ in patients suffering from CRC and healthy patients [19]. Due to dogs' ability to identify VOCs, they can detect tumours with a high degree of accuracy and even at early stages. These VOCs differ in each person, making up their olfactory fingerprint. They can be detected

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through breath or intestinal gas and have been analysed and found to be a tool of great potential, not only for the diagnosis of CRC but also for diabetes or Alzheimer's disease, among others [4,5].

Therefore, the analysis of gases from both the breath and the stool or changes in stool temperature can provide evidence to help to design a system capable of early detection of diseases such as CRC, with many advantages over the early detection tests which have been used to date [16].

An analysis of the low-cost systems currently available for population screening has shown that the main methods for early detection are fecal occult blood test (FOBT), colonoscopy, sigmoidoscopy, faecal immunochemical test (FIT), stool DNA testing and computed tomography colonography [3]. FOBT is the test of choice because of its lower cost compared to other screening tests. However, it requires good infrastructure, a large amount of material and human resources (administrative staff, nurses, digestive tract specialists, anaesthesia, preventive medicine, etc.). All this has a high cost for the healthcare system [18]. In recent years, the Internet of Things (IoT) has emerged as a new paradigm which can overcome these limitations and which has been of great use to the healthcare sector [1,12,13,20]. Among the many benefits that this paradigm brings to the healthcare sector are cost reduction and real-time monitoring.

This work proposes an initial system prototype based on the IoT paradigm to monitor the stool of patients at home with the aim of being the first prototype to detect anomalies. The initial system prototype will be composed of different development boards, sensors and actuators which will be placed on the toilet lid to collect data of interest related to gases and thermal images. The data collected by the sensors will be sent by wireless means to a central sink node which will store the information in a cloud server for persistence and send the information to an IoT platform for display. The main advantages of the proposal are that it is small scale, low-cost and non-invasive, with low power consumption.

The structure of this paper is as follows. Section 2 reviews the works related to gas and temperature monitoring for the early detection of diseases and low-cost monitoring systems for disease prevention or diagnosis. Section 3 presents the architecture of the system, describing all its components and the information flows within the system. Section 4 sets out the information processing proposed for the collection of sensor data, persistence in the cloud server and data display on the IoT platform. Finally, Sect. 5 presents the conclusions drawn and future lines of work.

2 Related Works

This section reviews the literature on the use of devices, sensors and intelligent systems to monitor gases and temperature for the early detection or diagnosis of diseases. To this end, firstly, we will review works related to devices with gas and temperature monitoring sensors for the early detection of diseases and, subsequently, systems which use sensors of this nature.

2.1 Gas and Temperature Sensor Devices for Early Detection of Diseases

The literature has shown the importance of gas sampling and stool temperature monitoring as fundamental functions to be implemented in our IoT system.

Regarding devices that monitor gases, the work presented by Malagú et al. [11] gives clues on the detection of VOCs. They use a series of MOX (Metal OXide, metal-oxide-semiconductor type) sensors which can detect VOCs even in conditions of low and high humidity and in low concentrations.

Benara et al. [2] show the first steps taken to manufacture a sensor capable of detecting methane (CH_4) at low concentrations. Analysis of this gas could be useful for identifying patients suffering from CRC. One disadvantage would be related to breath samples, which may require previous drying.

Movilla-Quesada et al. and Hofstetter et al. [7,14] present the use of MQ sensors for the collection of measurements of different types of gases in different projects such as the analysis of greenhouse gas emissions in asphalt mixtures with recycled materials or for the analysis of ammonia concentrations in the environment and its possible effects on poultry.

In terms of temperature monitoring, thermal cameras are an excellent option for the detection of a multitude of health-related problems [8,9], as well as being a good low-cost option [17]. Kaczmarek et al. [8] review the use of thermal cameras in medical applications such as analysing the severity of a body burn and its healing or the healing of a wound after cardiac surgery. All this has been validated by obtaining thermal camera images in different clinical studies.

Lahiri et al. [9] review medical applications where the successful use of thermal cameras has been proven for the diagnosis of breast cancer or diabetes related to vascular disorders as well as applications in dentistry, for example, for the determination of the common cracked tooth syndrome, which is very complicated to diagnose. Another use is the detection of fever, the most common symptom of COVID-19, with the aim of preventing massive spread of the virus.

2.2 Low-Cost Monitoring Systems for Prevention or Diagnosis of Diseases

In view of the type of commercial sensors which could be compatible with our purpose, a review of the corresponding literature has been carried out. Some of the most prominent examples are shown below.

In the literature, it is quite common to find the use of E-Nose technology for the design of disease prevention or diagnosis systems. This type of E-Nose technology simply consists of an array of sensors, usually MOX type sensors, with the ability to detect different types of VOCs. Liu et al. [10] designed a diabetes diagnosis system, from which the breath of participants was analysed to decide whether they were suffering from diabetes.

The analysis of VOCs for the early detection of cancer has also been studied by Thriumani et al. [21] to try to detected lung cancer based on an already marketed E-Nose and using classifiers for machine learning. To do this, samples of cancerous cells from both breast and lung cancer were cultivated and analysed by the E-Nose together with healthy cells, showing that it is capable of identifying a high percentage of healthy or cancerous cell tissue.

Finally, given the recent coronavirus disease 2019 (COVID-19), work has been carried out on monitoring systems in this highly topical area. Ullah et al. [22] try to monitor the state of health of a patient with COVID-19 and also check whether their quarantine is being carried out correctly. This is done through electrocardiograms (ECG), blood oxygen measurements (SpO_2), body temperature, respiration sensors, accelerometers and gyroscopes. The collected data is sent to a cloud server where it is analysed using machine learning techniques and previous historical data. In addition, through a web application, they displayed the data analysed by their system and showed it to professionals and even to the patients themselves.

Thanks to the literature, it was possible to gain insights such as what type of VOCs are related to CRC, that MOX-type sensors are the most suitable for detecting VOCs and that VOCs from the intestine do not need a previous preparation phase, which are fundamental aspects for the design of our IoT system.

3 Architecture of the System

In this section, first of all, the architecture of our initial system prototype is presented, which will be composed of the different development boards, sensors and actuators in charge of collecting the key data (gases and thermal images) of the depositions from the toilet lid. Subsequently, we show how this data has been serialised and transmitted wirelessly to a central sink node, which will store the data in a cloud server for data persistence while sending the information to the IoT platform for visualisation.

In this overview in Fig. 1, it can be seen that the initial system prototype is made up of two very different parts: hardware and software. Both are responsible for ensuring that the system meets our key objectives.

The hardware is made up of the following elements:

- **Lolin32 Lite (ESP32) development board:** The main function of this board is to be the master of the NodeMcu V3 and to send the signal which interrupts the sleep mode (deep sleep mode) of the NodeMcu V3, thus reducing consumption considerably, as well as to process the alarm signal of the passive buzzer. This module already incorporates Wi-Fi, which will be very useful for transmitting the data collected (referring to user interaction with respect to the start and end of sample collection) without the need to purchase an external module, simplifying the process of building the initial system prototype. Another advantage is its Serial-USB converter, which allows the board to be connected directly to the computer for programming.
- **NodeMcu V3 (ESP8266) development board:** The slave. This development board model was chosen due to the need to supply 5 V to the gas sensor and it has a 5V output pin. As well as its small size, like the previous

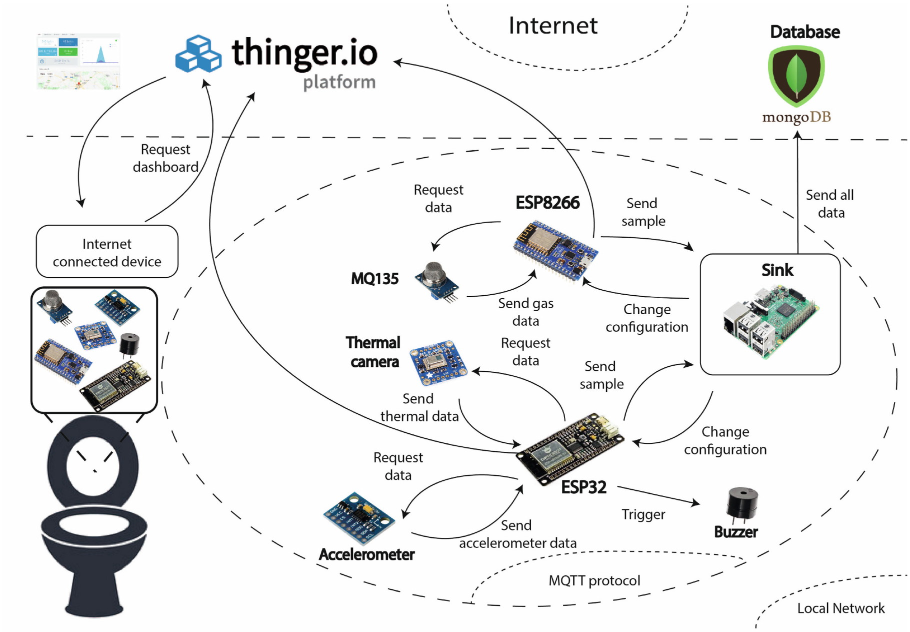

Fig. 1. Initial system prototype diagram

board, it incorporates Wi-Fi and a Serial-USB converter which allows it to be powered and programmed. The Wi-Fi feature has been a determining factor in our decision to choose this model among all the possibilities offered by the market.

- **Raspberry Pi 3 Model B+ development board:** Its main advantage is its significant computational capacity for its small size. Its purpose is to manage the data flow between the ESP32 and ESP8266 boards (the so-called central sink node).
- **Adafruit AMG8833 IR thermal camera sensor:** This sensor is formed by an 8×8 matrix of infrared thermal sensors, providing a low-resolution image of the deposition made by the monitored person. Its low resolution (8×8 pixels for a total of 64 pixels) could be thought to be a limiting factor; however, in our initial system prototype, given the nature of the images to be captured, it is actually an advantage as it provides anonymity, protecting the privacy of the monitored individual. Additionally, this type of infrared image capture device currently has a high cost, which tends to increase proportionally as the resolution increases. Given its limited resolution, the price of this sensor has been significantly reduced.
- **Accelerometer sensor MMA8451:** This sensor detects movement, tilt and orientation. It was included in the initial system prototype to determine when the person to be monitored is ready to use the toilet. Its purpose is to determine the start and end of the action in order to increase sample

collection and determine the time elapsed, giving the alarm signal with the passive buzzer.
- **MQ2 gas sensor:** It measures the concentration of different gases present in the air. It is a MOX sensor and can detect Liquefied Petroleum Gas (LPG), smoke, alcohol, propane, hydrogen, methane and carbon monoxide, making it useful for collecting gas samples in depositions. One of the major disadvantages of using this sensor was its power consumption, which is 150 mAh. Although this may seem small considering that it is a battery-powered system, this is a factor to be taken into account.
- **MQ135 gas sensor:** Allows detection of ammonia, benzene and alcohol gas, but is also sensitive to smoke and other toxic gases.
- **Passive buzzer:** This actuator, which transforms electrical signals into sound waves, has been used to alert the monitored person that the data collection is complete and the toilet can now be flushed.

The software is made up of the following elements:

- **Visual Studio Code:** This is the chosen environment to program the ESP32 and ESP8266 development boards, as it offers more advanced functionalities than the common Arduino IDE and can be complemented by adding extensions. In our case, we have added C++, Python and PlatformIO IDE.
- **MongoDB:** This NoQSL database is usually used for IoT data management, the different entities have been stored in it. This database provides a number of advantages: it allows the creation of indexes to speed up searches, which is very useful when the volume of data is significantly large, it has tools for automatic data analysis, due to its focus on IoT, and thanks to the fact that it is a document-based data model, it allows the definition of structures that group different fields.
- **Thinger.io:** IoT platform used to display the data collection in real time, through visual elements such as line graphs, among others. Although it is a commercial tool for which we must purchase a licence, the free version that allows us to connect up to two devices (gas sensor MQ2 and MQ135) has been more than enough in this prototype.

3.1 Data Transmission

The protocol used is the Message Queuing Telemetry Transport (MQTT), a network protocol based on publication and subscription that is ideal for low-resource devices such as our development boards. To implement this protocol in our initial system prototype we have used a library developed for that purpose [15]. However, it has disadvantages such as not allowing the configuration of access control to the server through certificates or the Quality of Service (QoS) of the messages. The format of the data packets exchanged via MQTT contains:

- An initial part found in all types, called fixed header. Among the information it can provide is the QoS, the type of message or the number of bytes of the remaining packet.

– A variable header only present in some MQTT packets.
– A payload, also optional, of variable length and with all the information to be sent.

Using this protocol, the development boards publish the data collected by the sensors and the Raspberry Pi is in charge of subscribing to access this data.

3.2 Data Serialisation

The device will have to transmit the collected data to an external platform via Wi-Fi connection. By serialising the objects within the memory to convert complex structures into text strings, it is possible to send all the data in a single message, considerably reducing the subsequent processing of the data and therefore reducing the load on the MQTT server. The Java Script Object Notation (JSON) text format has been used, which provides multiple advantages: it is easy to understand, lighter in transmissions, and has high processing speed.

4 Information Processing

This section presents the proposal for processing the information in our initial system prototype. For this, firstly, the data collection process is described, followed by how this data is stored for persistence, and finally, how it is displayed using an IoT platform.

4.1 Data Collection

Having broadly discussed the protocols, connections and data format, the steps to be followed in collecting the data are:

– When the monitored person opens the toilet lid, the ESP32 (master) sends a signal to the ESP8266 (slave) for connection to the Wi-Fi network, the MQTT server and the Thinger platform.
– Data from the gas sensor is collected and sent until the ESP32 sends an end of action signal to the ESP8266 when the monitored person lowers the toilet lid.
– The ESP8266 disconnects and enters deep sleep mode until the ESP32 restarts the cycle, returning to step one.

Another mode of operation with programmed data collection regardless of the person to be monitored has also been implemented. This operating mode starts when a predetermined time is reached, as long as the ESP8266 board is in deep sleep mode. Then, an image of the values detected by the gas sensor is captured. This sample collection is performed every 60 s, although this parameter can be modified in the configuration file. This mode of operation is required to regularly monitor the values under “normal” and “abnormal” conditions. An “abnormal”

Fig. 2. Final prototype

condition could be the use of cleaning agents in the toilet, whose gases could persist after use and thus significantly alter the actual values (Fig. 2).

The sensors used (MQ2 and MQ135) have required the use of a library for their implementation [6] to find out which gases play the most relevant role in this type of detection. Obtaining measurements from this type of sensor is very simple, but obtaining accurate measurements requires preparation, taking into account the preheating time, which can range from minutes to hours.

Concerning the MQ135 sensor, it must be taken into account that the CO2 measurements in normal conditions are 400 parts per million (ppm) and this is the baseline for our reading value collected in the ADC (Analog-to-Digital Converter) of the ESP8266, so in the library it is always increased by 400 to produce the real value.

To avoid applying any type of formula, the sensor data can be read in raw values. This is what we have done in this project, carrying out a study to identify the threshold that detects whether the user is making a deposition or not.

These collected values require further processing, taking into account that the ESP8266 has a resolution of 10 bits, and that the voltage provided by the sensor will be a value between 0–1024. If we want to obtain the number of ppm, a simple conversion is carried out, as the minimum to be detected is 300 ppm and the maximum is 10000 ppm.

Regarding the number of samples to be collected with the sensor, intervals of one second have been estimated to be the most appropriate. However, this parameter can be modified in the configuration file. It should also be taken into account that measurements are collected every second even if the user is not using the toilet.

The temperature data obtained from the thermal camera, on an 8×8 matrix, was used to perform the analysis. It was then transformed into images for debugging to check that the camera was working correctly. To transform temperature data into images, a simple procedure has been followed whereby the minimum temperature value is associated with a colour value and the maximum temperature value is associated with another colour, along with an intermediate colour scale for intermediate temperatures.

4.2 Database

As mentioned previously, the database chosen is MongoDB. Four unrelated entities were used to store the information. As for the entities, we have selected thermal data, data for the opening of the lid, values obtained by the gas sensor (raw readings) and finally, test results with the MQ135 and MQ2 sensors. These are sent using JSON format and each data collection will have its own structure. However, they will all have the following fields in common in the structure: an identifier (id), the name of the sensor, the measurement and the date of collection. Table 1 shows some of them.

Table 1. Data collection for the entity THERMAL DATA and USE DATA.

Thermal data	Description	Variable type
Id	Unique identifier	ObjectId
Sensor	Sensor identifier	String
Thermal array	List of temperature values collected by the sensor	Array
Img id	Image sequence number	Integer
Control data	Indicates whether the data is a control sample	Boolean
Date	Date and time in international format	ISODate
Use data	Description	Variable type
Id	Unique identifier	ObjectId
Sensor	Sensor identifier	String
Toilet id	Indicates whether the toilet lid has been opened or closed	String
Minutes	Number of minutes the lid has been open	Integer
Seconds	Number of seconds remaining	Integer
Date	Date and time in international format	ISODate

4.3 Data Visualisation as Decision Support for Detection

As discussed in previous sections, the IoT platform that has been chosen is Thinger.io. Figure 3 shows the dashboard created to display the data on Thinger.io. This dashboard is composed of three line graphs: the first one shows the history of maximum and minimum temperatures recorded by the thermal camera, the second one shows the history of values collected by the gas sensor and a third one represents the toilet usage log. Two meters have also been included, one to show the last raw value obtained by the gas sensor and the other to show it in ppm units.

Fig. 3. Dashboard

5 Conclusions

In this work, we have proposed a first prototype of a system to monitor from home the stool of patients with the aim of creating a first prototype to detect anomalies. To do this, firstly, the architecture of the system has been presented, consisting of the development boards, ESP32 and ESP8266 (both located on the lid of the toilet and responsible for collecting data), as well as Raspberry Pi 3 (the central sink node), the MQ2 and MQ135 sensors, the thermal camera and the passive buzzer actuator. Subsequently, the protocol for wireless data transmission was presented, where limitations were found as the ESP32 has random wireless connection losses due to an error in the libraries to establish the connection and the MQTT broker slows down if the time between sample collection decreases. Finally, the processing carried out from the data collection has been proposed for its subsequent storage in the MongoDB database, which provides data persistence, and visualisation on the IoT platform Thinger.io.

This prototype stool gas and temperature monitoring system aims to be a first step in the early detection of cancer. It is clear that the creation of such low-cost IoT systems to monitor VOCs not only in stool but also in exhaled air samples is a great step forward in this area and could reduce the mortality rate of this type of tumours, which, if detected early, are more likely to be treated successfully. In addition, it is an example of the benefits of bringing IoT and health together. Our future work focuses, on the one hand, on testing the initial prototype with cancer experts with the aim of a clinical trial, taking into account the variability of the population (control group) and the different places where it will be performed (clinic, laboratory or home), and on the other hand, on the challenge of finding sensors with greater range, sensitivity and accuracy to improve the current prototype.

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