Water quality monitoring system

David Carpinteiro Mendes
Instituto Superior Técnico, Lisboa, Portugal

Abstract

Water pollution in urban streams and rivers has increased in the last decades. Despite improvements in the last few years, pollution from diverse urban activities is still reaching the watercourses and affecting the water quality. Because of this, methods for detecting pollution sources and assessing the water quality of the streams are needed. Traditional water quality monitoring by chemical analysis in laboratories is revealing to be not suitable since it is expensive and only gives information about the instant of sample collection. The way to overcome this limitation is to implement continuous sample stations, that are currently only available in expensive commercial systems. To solve this problem, this thesis proposes a low-cost prototype station capable of continuous monitoring. The prototype will implement six low-cost sensors, including a state-of-the-art low-cost spectral sensor, that will measure five physico-chemical parameters and the spectral response of the water. The station will measure the water at regular intervals of time and send the information to a web server. A dashboard displays the data collected by the station and enables the creation of notifications to alert the user of changes in the water quality. This prototype station, together with the data collected will provide a useful tool to assess the water quality of urban streams and enable better governance and more efficient territory management.

Keywords: water pollution, optical sensors, internet of things, low-cost monitoring.

I. INTRODUCTION

Pollution in urban water streams and rivers is a known problem and has increased in the last century [11]. Although domestic water sewage systems have improved significantly, water quality degradation still occurs, generating negative impacts on the surrounding ecosystems [16]. Pollution from diverse activities still reaches the watercourses via run-off within the watershed, or drainage area (diffuse pollution), and via point source discharges [6].

The nature of diffuse pollution is mostly controlled by land uses occupying different areas within the watershed, which, after precipitation events, will drain to different river segments. For urban areas, the rainfall often drains through roads and other impermeable paved surfaces, transporting specific pollutants. On the other hand, agricultural land uses mostly enhances soil erosion which leads to sediment outflow as well as fertilizers (e.g., nitrogen and phosphorous lixiviation) [5], [3], [14]. Point source pollution sources normally have a high concentration of either organic compounds derived from urban effluents or a high concentration of metals and inorganic substances derived from industrial effluents [7].

Given the vast and complex relations between urban areas' pollution sources and watersheds, it is difficult to assess stream/river water quality. The most common type of sampling for water quality is random or systematic infrequent sampling. Traditional water quality monitoring in Portugal is based on weekly water sampling and chemical analysis in laboratories following specific procedures to reduce sample contamination/degradation. This method is not only expensive and time-consuming, but it also provides an assessment of the water quality limited to the instant of collection. In addition, these water quality monitoring surveys do not provide analytical results in a timely manner to clearly identify pollution sources and effects [18].

One way to resolve this is by frequently (e.g., <1-hour intervals) monitoring water parameters in different points along a stream/river, strategically placed to detect pollution sources based on drainage area land use (for diffuse sources) and location of major industries or other infrastructures with pollution potential (for points sources). Contrarily to random or systematic infrequent sampling, the latter being the most common, continuous sampling detects water chemical and/or physical changes which are very important in highly dynamic urban areas. Currently, continuous sampling is implemented via commercial solutions, which include physical parameters (such as temperature, turbidity, solids, and electrical conductivity), and its integration is expensive and not scalable [5].

With recent advances in electronic technology, sensors that can detect changes in water quality have become more accessible. Relatively cheap and low complexity systems have been used to monitor changes in water parameters several times a day and even to notify an operator when there is a parameter change that indicates water quality degradation [17]. Recent work showed that these systems can provide an affordable and useful tool, providing remote and real-time results with respect to water quality measurements.

The main objective of this work is to develop a low-cost water quality monitoring system, with these new sensors and technologies, to be deployed in urban streams. This system must be cost-effective and, at the same time, be able to provide real-time monitoring, with a high sample frequency, of the stream water quality. Being cost-effective will enable the system to be used in several locations (for example, along a watercourse). The high sampling frequency will help detect contamination events, that occur fast and disperse rapidly, along the water body. The developed system, in particular, any implemented sensors, should also alert to changes in water parameters reflecting a possible ongoing input of pollutants upstream, and the need to proceed to immediate sampling and laboratory analysis as well as mitigation measurements in extreme cases (for example reduction of pollutant concentration by adding water from the utility network).

II. WATER POLLUTION

Water quality in watercourses, in particular, rivers, lakes and other freshwater bodies can be assessed by monitoring their main characteristics: hydrodynamic, physical and chemical, and biological quality [20]. In urban areas, water quality assessment becomes more difficult given the multiple sources of pollution, from sewage overflow during storms to inadequate urban planning, which resulted in old sewage systems being built parallel to the streams, leaking the contents into the streams, when broken. Adding to these problems there are also the unpredictable illicit waste discharges that often occur during the night, at weekends and during high flow events [5]. Waste and other products of anthropogenic activity are released into the environment in multiple forms and reach the aquatic bodies. These can be classified into two main categories: point sources and non-point sources (diffuse sources). Point sources have the most evident impact on watercourses, due to the abrupt discharge with high pollutant concentrations. On the other hand, in spite of being less obvious due to a typical lower concentration of pollutants, frequently diluted in rainwater, diffuse sources are more dominant [7], [5], [20].

III. NEW TECHNOLOGIES FOR WATER QUALITY MONITORING

According to the published literature, the use of new technologies in water quality assessment, in particular IoT technologies, has been growing in the past decade. Although, since the start of the century there has been some work on developing new and low-cost technologies to measure water quality, only in the last few years there has been an increase in the development and deployment of such systems [8]. Of these systems, fourteen were deployed in recent years (2017-2021). This shows a growth originated from the recent need for monitoring water quality and also shows the increasing accessibility to both WSN and water sensors technologies. Most of these systems use IoT technologies and often monitor basic water parameters like pH, temperature, turbidity or EC.

III-A. MCUs

The most common Microcontrollers technologies are presented next, together with their capabilities.

- **AVR** is an 8-bit microcontroller architecture, widely used in the Arduino platform. The atmega328 and atmega2560 are the most used MCUs.
- **ESP** is a series of MCUs that integrates low power consumption and IEEE 802.11 (Wi-Fi) radio capabilities.
- **ARM** MCUs are typically 32-bit and provide more processing capabilities than 8-bit microcontrollers. The RP2040, the teensy family and the STM32 family are some examples.
- Raspberry pi's are microcomputers that have integrated IEEE 802.11 (Wi-Fi) and IEEE 802.15 (Bluetooth) capabilities. The boards more suitable for IoT are the Raspberry pi nano W variants.

III-B. Sensors

Sensors have become cheaper in recent years and new technologies have been developed that make detection of other parameters in addition to the classic water parameters. The most used water sensors will be explained in detail in the next lines.

- pH sensors can be of four main types, optical and fluorescent sensors, electrodes with pH-sensitive polymers, potentiometric sensors and miniaturized pH sensors [9].
- Temperature sensors can be of several types, but the most common are RTD, thermocouples and thermistors [1]. Although, thermistors are the most common and affordable type, in recent years smart low-cost digital sensors have become available, these sensors integrate the temperature measurement into a single small footprint package and output a digital signal with the temperature value [13].
- Turbidity sensors provide an indication of the level of turbidity of the water. These sensors are usually very simple and use a LED and a phototransistor to output a voltage level that is proportional to the light that passes through the water.
- Electrical conductivity sensors are conductometric sensors that work by measuring the resistance between two electrodes. To perform this measurement an excitement current is needed, this current is usually generated by an AC source. Then, using a Wheatstone bridge, a voltage value is measured and translated to an EC value.
- Dissolved oxygen sensors indicate the level of oxygen dissolved in the water, typically as a percentage. The most used dissolved oxygen sensors are based on the Clark sensor. These sensors have a membrane permeable to gas, that allows the oxygen to enter in contact with the electrodes,

producing a current that is translated into a voltage, which is proportional to the oxygen levels in the water.

- Low-cost spectral sensors are the state of the art imaging sensors for detecting reflected light. These sensors have small sensor dies with photodiodes that are sensitive to various wavelength bands. These sensors can be combined to achieve a broad sensing region from UV to IR. These sensors also generate the wavelengths that will be absorbed or reflected, typically with white, IR and UV LEDs.

III-C. Communication

Several Communication technologies and protocols have been developed in recent years to achieve the needs of IoT devices, mainly low power consumption and long-distance coverage [12]. These new technologies vary both in range, data rate, power consumption and cost, as illustrated in figure 1. The most common communication technologies are presented below, together with a brief explanation of their capabilities.

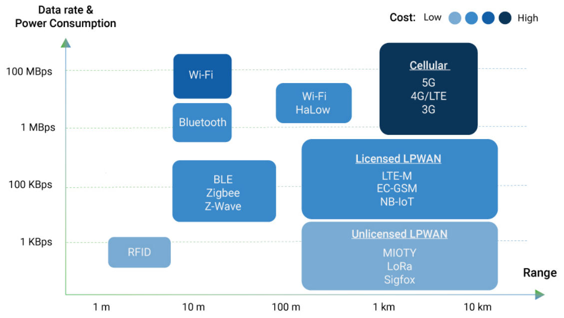

Fig. 1. Comparison of the different IoT network technologies. Image source:[10]

- IEEE 802.11 or Wi-Fi is a WLAN. These networks are usually used in local areas having a range of 100-1000 meters. Wi-Fi is usually the main network for devices to access the internet, but given that it is already present in most infrastructures it is widely used in IoT devices.
- IEEE 802.11 (Zigbee) is a WPAN with a short range of 10 to 100 meters. This network is similar to IEEE 802.15 Bluetooth but has characteristics that make it suitable for IoT devices. It provides low power capabilities and offers mesh capabilities which can increase its range from short to medium, or even longer.
- Cellular (2,3G,4G,5G) networks provide voice and data services. Given that are well established in urban areas, they can provide good coverage, as well as a link capable of high data throughput, in particular when using the 4G and 5G.
- LPWANs, generally use communication protocols and frequencies that already exist, but are transformed into low throughput, long-range and low power communications. NBIot is an LPWAN based on cellular infrastructures (2,3G,4G,5G). Lora and Sigfox are other types of LPWAN based on Rf technologies, operating in the 868Mhz frequency range.

IV. SPECTRAL SENSORS

Low-cost sensors for water quality are emerging. Recently, new light sensors capable of spectral sensing have been released, making spectrometry affordable at a fraction of the price of commercially available spectrometers [19]. Among these sensors, there are two that have been used in the literature, although not in the water analysis field: the AMS AS7262 visible multispectral sensor, which captures six channels (at 450nm, 500nm, 550nm, 570nm, 600nm, and 650nm), and the AS7263 a red to near-infrared multispectral sensor, which also captures six channels (at 610, 680, 730, 760, 810 and 860nm) [15], [21], [2].

In this work, a new multispectral sensor was used, the AS7265x, that incorporates all the wavelengths obtained from the previously mentioned sensors, and extends further towards both higher and lower wavelengths. In this chapter, the methodology for determining the capabilities of this sensor, the AS7265x, in detecting pollutants in water is presented. The methodology consists of recording the spectral response of different solutions, where each solution has a fixed volume and contains a pollutant with a know concentration. The data is then analysed using statistical analysis to evaluate the detectable range of pollutants. These experiments are designed to assess the hypothesis that this new spectral sensor will be able to detect events of pollution, thus increasing the information collected by other common used water quality sensors like ph, electrical conductivity or temperature. The approach described here aims at detecting changes in these spectral responses for the different wavelengths and, at this stage of development, not to identify the pollutant itself. The spectral response of the AS7265x sensor is represented in figure 2.

The first approach to the experiments was to design a container where different solutions could be tested. The container had to be opaque to light and closed allowing only the light from the sensor LEDs to reflect on the solution, blocking outside light from interfering. To maximise the reflectance from the solution exclusively, the container walls were painted in black, so that the light reaching the container walls through the solution would be absorbed and not reflected back to the sensor.

The designed container was a cylinder, with a diameter of 104 mm and 135 mm of height, represented in figure 3. The container was initially designed to contain a volume of one litre, but following the results

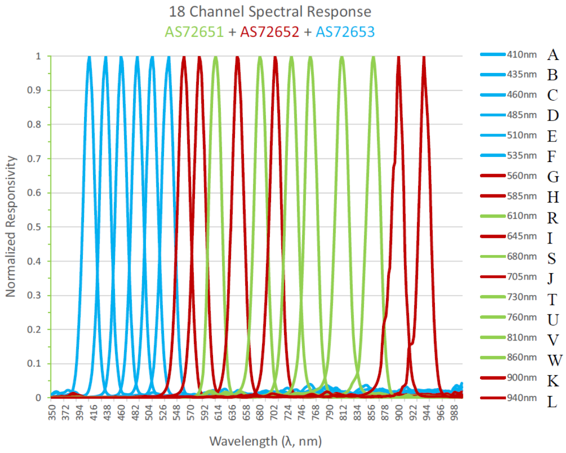

Fig. 2. AS7265x spectral response.

of other works using this sensor [4], it was found that the optimal distance from the sensor to the solution is approximately $1.5\,\mathrm{cm}$. To account for that, the volume of the tested solution was reduced to $900\,\mathrm{mL}$.

All the different pieces in this container were designed in CAD software and 3D printed using black PETG filament. All the parts were designed in Fusion360 and printed in the 3D printer Creality Ender 3 V2. After being printed, the container was waterproofed using clear epoxy and painted in black colour.

Fig. 3. The container used to perform the experiments.

To prepare and measure the solutions, the following experimental protocol was followed:

1) Dilute the initial quantity of compound into one litre of distilled water (solution 100%).
2) Transfer $900\,\mathrm{mL}$ into the container, and for each combination of LEDs (all, white, IR and UV) make three consecutive measurements, with the AS7265x sensor.
3) Transfer $100\,\mathrm{mL}$ of the previous solution and dilute it, adding $900\,\mathrm{mL}$ of distilled water (solution 10%).
4) Take $900\,\mathrm{mL}$ of that solution and put it into the container. Repeat the measurement as before.
5) Repeat steps 3 and 4, for the next two dilutions (1% and 0.1%).

This procedure was used for all the compounds except for the distilled water, used as a reference, and for the tap water which was not diluted.

IV-A. Results

The sensor response changed for all the pollutants, which indicates that the sensor detects these pollutants. Also, the response of the spectral bands varies between pollutants and along the different wavelengths, the higher values of reflectance are generally situated in the visible portion of the spectrum. In general, the response varies with concentration, the higher reflectances are associated with a higher concentration of pollutants. More specifically this response is more visible in white and green clay, soil, and sand. The higher reflectance associated with these pollutants is most likely related to the opaque nature of the solutions. All these contain sediments that do not completely dissolve in the distilled water and reflect more light than the remaining pollutants tested.

The distinct response in reflectance observed for different combinations of bands/pollutants/concentrations makes the resulting data hard to interpret using simple statistical approaches. The clear identification of pollutant/concentration based on spectral signatures is better addressed using robust statistical analysis/machine learning algorithms, which is beyond the scope of this work. However, these results represent a solid proof of concept and show that multispectral sensors provide information that can be used in water quality monitoring. As a final note, it is also important to state that these results are only valid for the specific types of pollutants and concentrations used in the experiments.

V. REQUIREMENTS

As stated before the main objective of this system is to automatically take periodically measures of water parameters and send them to a remote server. The system will be installed mostly in outdoor locations and as such it will be exposed to weather conditions. These locations can be remote, meaning access to electrical sources will be difficult and the cell network coverage will be limited. It will also need to be next to water streams where the terrain characteristics could be challenging. Some of these remote sites will also have poor accessibility's, being only accessible by foot.

Having this into account the system will need to have the following requirements:

- Sustain outdoor conditions since the system will most of the time be installed in an outdoor location, the system will need to be able to sustain rain, heat and other environmental conditions.
- Have good communication coverage, the system will need to send data and alerts to a remote server, this means the system needs to have good cell coverage even in the most remote locations.
- Easy to install in the field, the system must be easy to install in the field, depending on the system design, it must be easy for the operator

to deploy the system and turn it on.

- Compact and easy to transport, the system must be easy to transport to enable foot transportation to remote locations and must be compact to make installation possible in locations where there isn't much space available.
- Must be easy to replace the faulty components.
- Must be prepared to be powered by solar energy, the system will be deployed in remote locations where there isn´t access to normal energy sources, as such, the system must be prepared to be powered by batteries and solar panels.
- Collect data and provide a dashboard to not only visualize the collected data but also to notify about changes.
- Low cost, the system must use low-cost components to be affordable and enable multiple device monitoring.

VI. DESIGN

VI-A. Hardware architecture

The diagram of the system is represented in figure 4. In this diagram the blue dashed lines represent the water flow, from the stream into the containers and back to the stream, passing through the intake and outtake pump. This water flow design presents some challenges, namely the fact that the intake pump must be able to pump the water from a stream and take it up to the containers that can be a few meters up in height distance. The water components must also be able to address the problem of debris being pulled by the pump, by filtering or blocking them from entering the water loop.

The electrical architecture of the system is illustrated in figure 4. A standard 12 V PSU will be used. This PSU will provide power to the electronics and the actuators. The actuators will provide power to the water pumps. Depending on the location of the system, the system will work directly from the power grid (230V AC) or from an off-grid system with solar panels and batteries. Since the power supply choice is affected by the location, some electrical components of the system will also be affected, in particular the water pumps. With a standard installation that receives power from the grid, the pumps can be used at max power to pump the water. With batteries and solar panels, the energy available for the pumps will be far less, thus limiting the distance between the stream and the system. The actuators will be used to control the pumps, during the process of collecting data, emptying and filling the containers.

The electronic architecture is also represented in figure 4. These three components are relatively common in environmental monitoring systems. A single MCU will be responsible for controlling the system, more specifically coordinating the frequency of measurements, the pumps and the communication. This MCU will interface with the sensors, actuators and with the communication module. The sensors will be responsible for measuring the water parameters and the actuators will be used to control the water pumps. Finally, a communication module will allow for remote communication, regarding the communication, the protocol to be used should provide wide coverage and low power consumption, in the case the system is powered by batteries

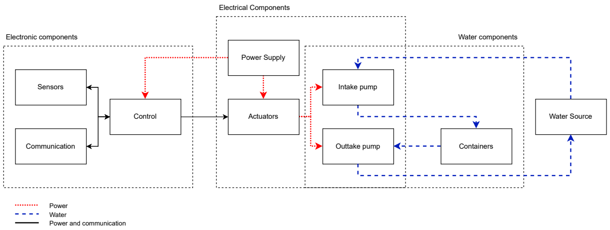

Fig. 4. Hardware diagram of the system

VI-B. Software design

The software will be divided into 5 generic modules as illustrated in figure 5. The user will access the UI module that represents the data received by the server. The server module has two main responsibilities, receive the data from the communication module and send this data to the UI. The communication module will provide the communication functionalities for the MCU to be able to send the data to the server. Finally, the MCU will be responsible for controlling the system and providing data to the communication module.

Fig. 5. Software modules

VII. IMPLEMENTATION

VII-A. Sensors

The implemented sensors are presented next.

- The temperature was one of the parameters we proposed to measure with this system, because of this a temperature sensor was needed. There is a broad selection of temperature sensors and technologies available. We opted to use the DS18B20 because this sensor is waterproof, is cheap and has an accuracy of $\pm 0.5\,^{\circ}\mathrm{C}$.
- To measure the water pH a pH sensor was needed. From the solutions available, the DF Robot, Gravity line, Analog pH v2 sensor was chosen because of its low cost and because it comes with two buffer solutions to calibrate the sensor.
- To measure the electrical conductivity of water an analog electrical conductivity sensor was needed. From the available options, the most suitable for our system was the EC v2 sensor from the DFRobot gravity line, this sensor provides laboratory-grade measurements, is low cost and

contrarily to other solutions has buffer solutions for calibration.
- To measure the water turbidity a turbidity sensor was needed. There were two available solutions, with very similar designs and characteristics. Ultimately the cheapest one was chosen, the analog turbidity sensor from the DFRobot gravity line.
- To measure the water TDS, the TDS sensor used was the Analog TDS Sensor from the DFRobot gravity line.
- The spectral sensor used was the evaluation board of the AMS optical AS7265x sensor from SparkFun Electronics.

VII-B. Boxes and containers

The system boxes were bought and modified to enable the installation of the different components. The dimension of the boxes are: bottom box, 327*240*190 mm and the smaller box, 242x184x60 mm. Two holes were made in this box to allow the water tubes to pass. The tubes were passed through two cable glands to prevent water and dust from entering the box. On the bottom part, eight holes were made to connect the four drain holes of each container. Lastly, 4 holes were made at the top part to mount the electronics box.

The model of the containers, with the system sensors, is represented in figure 6. These containers were modelled in CAD, as well as the sensors. This ensured the sensors would fit and would have enough space to not cause interference. The two containers are equal, the only difference is the lid which is different from the spectral sensor container to the other container. This also ensures other sensors can fit the system, with the only modification needed being a new lid, adapted to the new sensors. The containers were built with one intake hole and one drain hole. These are directly connected to the water pumps and fill and empty the containers. In addition to those, four safety drain holes were also implemented. These ensure that the containers will never overflow, which could cause problems in the sensors and pumps.

Fig. 6. The containers implemented in the system.

VII-C. Power supply and actuators

All the individual electrical and electronic components on the system, work with either 12 V, 5 V or 3.3 V. Since at the site of implementation we had access to 230V AC, we needed to transform the AC into DC. The decision to use an off-the-shelf 12 V power supply to convert 230 V AC into 12 V, was made because we needed 12V for the water pumps and because the MCU board in use could take an input of 12 V and step it down into 5 V and 3.3 V.

The PSU used takes as input an AC voltage of 230 V and outputs a DC voltage of 12 V. The max current is 5 A with a total power of 60 W. This power supply has 4 separated DC connectors that can be used to directly power the two water pumps and the MCU.

Since both water pumps work at 12V DC, and the MCU only provides an output of 5V, to control the pumps, an actuator must be used to switch each of the pumps on or off. To do this two relay modules were used, one for each pump. The relays in these modules, FL-3FF-S-Z-5VDC, are rated for a max voltage of 30 V DC with a max current of 10 A.

VII-D. Water Pumps

As mentioned before, because of the design, two water pumps were needed, one pump was needed to fill the containers, pumping water from the stream into the containers and another pump was needed to empty the containers, pumping water out of the containers into the stream.

The pump chosen to fill the containers was the CYBERNOVA 12V 131 PSI. This is a positive displacement pump that is relatively cheap and can provide the flow rate needed for the system. The pump chosen to empty the containers was the Anself QR50E. This is a centrifugal pump that is cheap and achieves a high flow rate with low power consumption. With this choice both pumps can be mounted inside the box, making the system more compact and the water can be pumped from a greater height.

VII-E. Controller and supporting electronics

The hardware diagram is illustrated in figure 7.

The MCU board used in this system is the SparkFun RedBoard Qwiic, this MCU is based on the Arduino UNO R3. This MCU board has six Analog inputs pins and 14 Digital IO pins. The system will need four analog pins for analog inputs, four digital pins for digital outputs, four digital pins for Serial0 bus and Serial1 bus, two analog pins for I2C bus and one digital pin for One wire bus.

Since the system will take measures timely, a way to store and keep track of time was needed. The solution that made sense, in this case, was to use an RTC. To choose a suitable RTC for this system two criteria were taken into consideration, the first was cost and the second was that the RTC must have a battery to keep track of time even if the system lost power. Of all the low-cost options available, the DFRobot I2C SD2405 RTC Module was chosen, although this module was not the cheapest available with a battery, it has a big advantage when compared to the rest, it uses a built-in rechargeable battery which means the battery will have a greater life than a typical non-rechargeable coil cell battery.

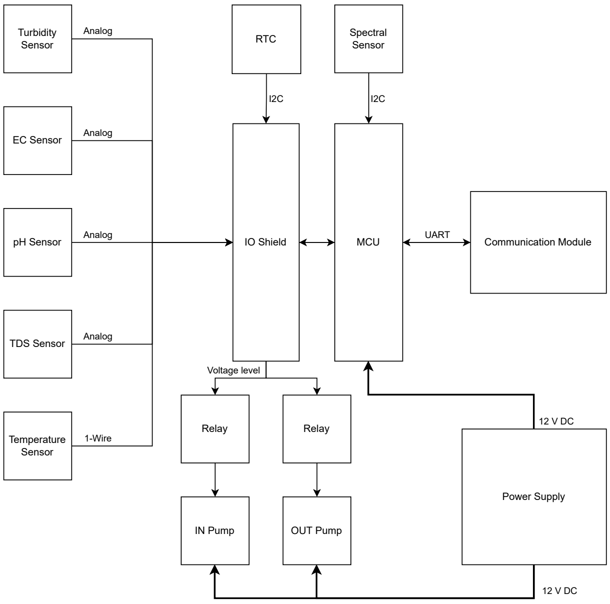

Fig. 7. Hardware diagram of the system

VII-F. Software

The MCU software diagram is represented in figure 8. The system starts by waiting for a message from the communication board, if this message is received within the timeout window the system syncs the RTC with the time received from the communication board, if not and the timeout occurs, the system will use the time from the RTC (**A**). After this initialization, the MCU starts the measuring cycle. The first step is to perform two cleaning cycles. During a cleaning cycle, the MCU turns the intake pump on and waits for the containers to fill, after waiting, the MCU turns the intake pump off and turns the outtake pump on, waiting for the containers to be empty, after this time the MCU turns the outtake pump off (**B**). After the last cleaning cycle, the MCU turns the intake pump on and waits for the container to fill before turning it off, after the containers are full the MCU gets each of the sensor values. Then sends a message to the communication board with all the data retrieved from the sensors (**C**). After this, the water in the containers is emptied, and another cleaning cycle is performed (**D**). After the cleaning cycle has ended the measuring cycle also ends and the MCU stays in the main loop, processing messages from the communication board until it´s time for another measure (**E**).

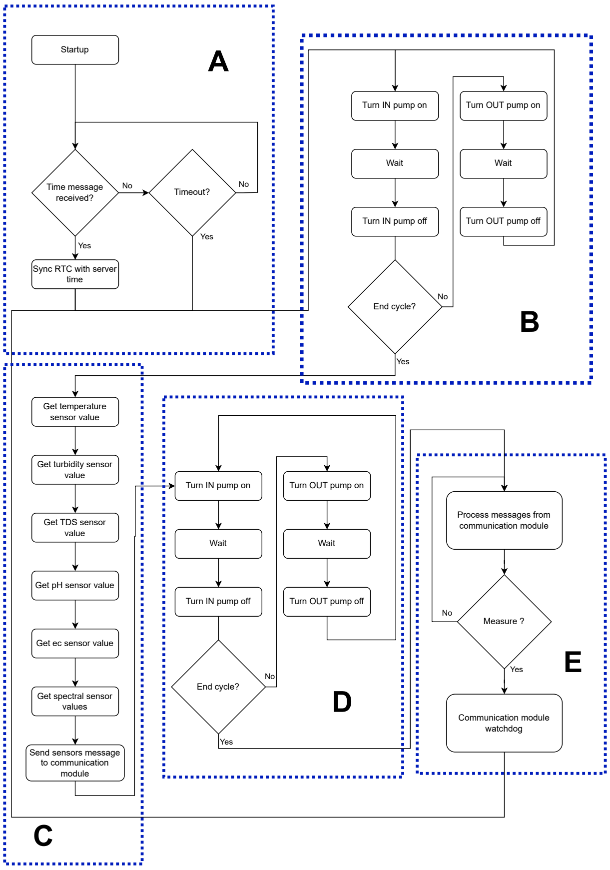

Fig. 8. MCU Software Diagram

The server consists of five main components, the COAP server, the API, the Database, a website and a visualization web application. Figure 9 illustrates the server architecture.

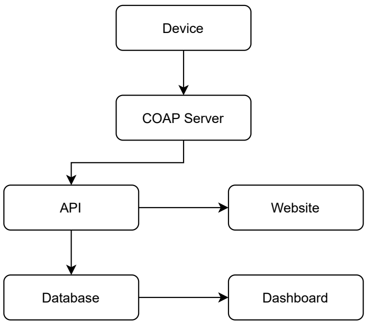

Fig. 9. Server Diagram.

VII-G. Communication

The board chosen was the Quectel BC66-TE-B, implemented as an individual module and programmed using the unofficial Arduino Quectel development platform. The board runs an Arduino code that handles all the communication and interfaces with the main microcontroller using a custom protocol through one of its UART interfaces.

The software architecture of the communication board is illustrated in figure 10. The board starts, after a certain period of sleeping, when it is necessary to send a new message. The MCU wakes the board by setting the board interrupt pin (D13) to HIGH. The system then initializes by trying to register in the network, if this is successful the board makes a GET request to a COAP server, to get the server time. Next, the board sends a confirmation message to the MCU and enters the main loop. When a message from the MCU with the sensor data is received the board computes the HMAC of the data and makes a PUT request with this data to the COAP server. After this, the board sends a watchdog message to the MCU, and checks for COAP request responses from the server. If the server time is received on one of these messages, a message time is sent to the MCU. After this, the board goes to sleep.

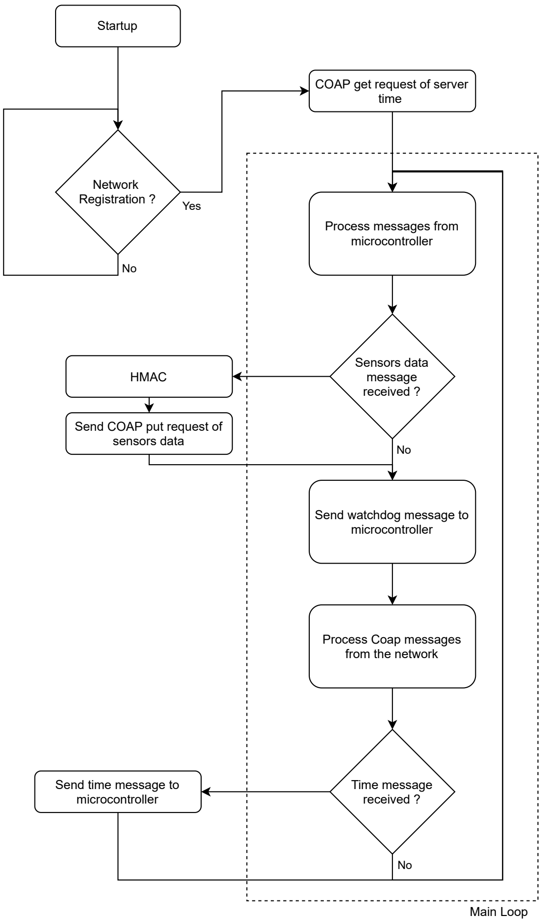

Fig. 10. Quectel BC66-TE-B Software Diagram

VIII. RESULTS

VIII-A. Development and Installation cost

The price of the prototype was 430.36 €, not taking into account the installation cost. The installation cost refers to the cost of the electrical installation, the cost of the pipes, the fittings, the one-way valve with the filter as well the cost of other accessories and parts. There are also other costs that could be added, the space allocation for the device, the cost of the electricity used and the maintenance costs.

VIII-B. Comparison

Compared to other existing low-cost solutions the system prototype developed has some differences. Starting with the sensors, and taking into account the most used sensors in these existing systems. This prototype implements the 3 most used sensors, pH, temperature and turbidity as well as the other two sensors in the 9 most used, the EC sensor and the TDS sensor. In addition to these sensors, the prototype developed in this thesis implements a spectral sensor that was not used in any of the existing low-cost systems. This sensor has the advantage of detecting pollutants in the water and not only parameter values like the other more specific sensors, used in the other systems.

Regarding communication, this prototype uses NBIoT. Compared with the other sensors we can see that no other system uses NBIoT. In fact, only 3 systems use cellular communication, with most of the systems using either Wi-Fi or Zigbee. Comparing this communication protocol with the cellular technologies, more specifically, normal data over 2G, 3G, 4G and 5G used in the other systems, NBIoT has a better range and also better battery consumption.

The MCU used in this system is the Atmega328p, and the evaluation board used is the SparkFun RedBoard Qwiic. This MCU is in accordance with the other systems, with the Atmega328p being the most used MCU in the existing systems. Comparing this microcontroller with the other most used pMCU and platforms in the other systems, more specifically starting with the second most used microcontroller, the 32-bit esp8266, this MCU has a higher frequency clock (80MHz) and uses more power than the Atmega328p, running at only 20MHz. The raspberry pi is the third most used, this microcomputer board runs a Linux OS, and the has a clock frequency of 1GHz, this makes this board use considerably more power when compared to the MCU used in this system the Atmega328p.

VIII-C. Deployment

Regarding the system installation, the system main box was placed in a higher place relative to the waterline, with protection from a gabion wall. This was done to protect the box from floodwaters and other debris that are brought in by flood currents in winter. The box was also tied to the concrete wall next to it to increase the protection and stability of the system. This was already equipped with a temporary power source that was installed with the help of CM Oeiras. The prototype station installed in the deployment location is illustrated in figure 11.

After the box had been fixed to the concrete wall, two tubes were run from the box to the stream. One to drain the collected water into the stream and another to collect the water. This last tube was longer, about 10 meters, and runs to the deepest part of the stream in that location. This ensures that even in summer when the water levels are low, the system can actively collect water for testing. This tube was also tied down to the stream shores in several anchorage points. These anchorages points were again done in the concrete wall that covers the shores of the stream in this specific location. On the end of this tube, a one-way valve was connected, together with a mesh filter. This filter prevents debris from the stream from entering the tubes, containers and pumps.

Fig. 11. Prototype station.

VIII-D. Data

The system was deployed in June 2021, and after some weeks of trials, the system began sending data consistently at the start of August 2021. As of the time of writing, the system is still sending data. The system sends data with a frequency of 30 minutes. The measurement data from the sensors is stored in a table. The table has at this time more than 10000 rows of data, each with 23 sensor values. To visualize this information, both in real-time and the past data, the dashboard illustrated in figure 12 is used. The dashboard shows at the top the most recent measurement and then further down presents a collection of graphs that shows the evolution of the parameters collected.

Analysing the collected data we can see clearly there are visibly difference in water parameters at times. Some of these differences are parameter spikes and also some variances of parameters that last a few days. This variance may indicate pollution events. There are also other variances that correlate with the atmospheric conditions. For example when it rains heavily the turbidity increases and the value of EC and TDS decreases.

This database can also be used in future to correlate the values collected with laboratory tests performed at the same time. Machine learning and artificial intelligence techniques can be used to predict and give warnings about water quality degradation or pollution events.

Last Measure: 2022-03-16 14:40:54

Temperature: 14.5 °C

PH: 4.11

Turbidity: 199 NTU

TDS: 436 ppm

Electrical Conductivity: 1.10 mS/cm

Fig. 12. Data visualization interface.

IX. CONCLUSIONS

This thesis's main objective was to propose and develop a low-cost system to automatically monitor water quality on a 24/7 basis. The system developed completed all its requirements and objectives. The system up-time was greater than 95%, not taking into account the initial weeks of testing and some maintenance where the system was kept offline. Regarding the requirements, the system was able to be deployed in outdoor conditions and sustain the weather conditions without the normal working behaviour being affected. Communication-wise the prototype worked without problems, since the prototype was deployed in an urban area the range was not an issue and the communication module worked flawlessly. The system was also easy to install on-site, with the first installation taking some hours of work. It is also fairly easy to transport and move to other locations if needed, with the only more fixed part of this project being the pipes. In regards to the system being prepared to use solar power and batteries, the system is prepared, considering the system's main voltage is 12V DC and most small solar panels systems work with either 12V or 24V, it will be an easy modification.

Regarding the server-side of this project, all the different components were implemented in docker containers and worked without problems. These containers also make the transfer of the server architecture to other infrastructures easier.

The dashboard website created also fulfilled the project objectives, it shows the water parameters in real-time and also enables the user to view past in form of graphs.

Overall, this system fulfilled all of its objectives and requirements. Providing a low-cost IoT system that can be used to assess water quality with the help of classical low-cost sensors and innovative ones never used before like the multi-band spectral sensor.

X. FUTURE WORK

The raw data produced by the system could be used in future execution of machine learning algorithms. Municipio de Oeiras (CMOeiras) collects frequently, at the same site where the prototype is installed, water samples to be analysed in a laboratory. The results of those analyses could be used as train and validation sets for a future machine learning system.

The periodic collection of data using the prototype implemented, and its availability in a simple way (e.g. using Grafana dashboards) could be used as a source of information for the decision-makers, enabling better governance and more efficient territory management. Also, the configuration of the system to generate alerts when determined parameters reach certain thresholds could be another innovative functionality in the area of governance.

ACKNOWLEDGEMENTS

The author would like to thank the supervisors, Prof. João Silva and Helena Serrano, for their help and guidance throughout this project, Maria Alexandra Oliveira for all the help provided, CM Oeiras for providing the space and the conditions for installing the prototype station and Altice Portugal for providing the communication board and SIM card.

REFERENCES

[1] B. Arman Kuzubasoglu and S. Kursun Bahadir. Flexible temperature sensors: A review. *Sensors and Actuators, A: Physical*, 315:112282, 2020.

[2] I. Bhati and M. Bhattacharya. An IOT-Based System for Classification and Identification of Plastic Waste Using Near Infrared Spectroscopy. In S. Kundu, U. S. Acharya, C. K. De, and S. Mukherjee, editors, *Proceedings of the 2nd International Conference on Communication, Devices and Computing*, pages 697–703, Singapore, 2020. Springer Singapore.

[3] W. E. Bullard. Effects of land use on water resources. *Journal of the Water Pollution Control Federation*, 38(4):645–659, 1966.

[4] R. I. Chowdhury, K. A. Wahid, K. Nugent, and H. Baulch. Design and Development of Low-Cost, Portable, and Smart Chlorophyll-A Sensor. *IEEE Sensors Journal*, 20(13):7362–7371, 2020.

[5] A. M. Duda, D. R. Lenat, and D. L. Penrose. Water quality in urban streams - what we can expect. *Journal of the Water Pollution Control Federation*, 54(7):1139–1147, 1982.

[6] J. Fawell and M. J. Nieuwenhuijsen. Contaminants in drinking water. *British Medical Bulletin*, 68(1):199–208, 2003.

[7] A. C. P. Fernandes, L. M. de Oliveira Martins, F. A. L. Pacheco, and L. F. S. Fernandes. The consequences for stream water quality of long-term changes in landscape patterns: Implications for land use management and policies. *Land Use Policy*, 109(2021):105679, 2021.

[8] J. O. Ighalo, A. G. Adeniyi, and G. Marques. *Internet of Things for Water Quality Monitoring and Assessment: A Comprehensive Review*, pages 245–259. Springer International Publishing, Cham, 2021.

[9] O. Korostynska, K. Arshak, E. Gill, and A. Arshak. Review on state-of-the-art in polymer based pH sensors. *Sensors*, 7(12):3027–3042, 2007.

[10] M. Kumhar and J. Bhatia. *Emerging Communication Technologies for 5G-Enabled Internet of Things Applications*, pages 133–158. Springer International Publishing, 1st ed. edition, 2021.

[11] J. C. López-Doval, A. Ginebreda, T. Caquet, C. N. Dahm, M. Petrovic, D. Barceló, and I. Muñoz. Pollution in mediterranean-climate rivers. *Hydrobiologia*, 719(1):427–450, 2013.

[12] M. S. Mahmoud and A. A. Mohamad. A Study of Efficient Power Consumption Wireless Communication Techniques/ Modules for Internet of Things (IoT) Applications. *Advances in Internet of Things*, 06:19–29, 2016.

[13] K. A. A. Makinwa. Smart temperature sensors in standard CMOS. *Procedia Engineering*, 5:930–939, 2010.

[14] A. Müller, H. Österlund, J. Marsalek, and M. Viklander. The pollution conveyed by urban runoff: A review of sources. *Science of the Total Environment*, 709:136125, 2020.

[15] A. N. Yumang, A. D. Nieva, K. G. Lomotan, and A. III R. Jerez. Application of Spectral Sensor in Determination of Uric Acid Levels. In *2021 11th International Conference on Biomedical Engineering and Technology*, ICBET '21, pages 133–138, New York, NY, USA, 2021. Association for Computing Machinery.

[16] R. J. Naiman, S. E. Bunn, C. Nilsson, G. E. Petts, G. Pinay, and L. C. Thompson. Legitimizing fluvial ecosystems as users of water: An overview. *Environmental Management*, 30(4):455–467, 2002.

[17] M. Pule, A. Yahya, and J. Chuma. Wireless sensor networks: A survey on monitoring water quality. *Journal of Applied Research and Technology*, 15(6):562–570, 2017.

[18] Y. Qin, H. J. Kwon, M. M. R. Howlader, and M. J. Deen. Microfabricated electrochemical pH and free chlorine sensors for water quality monitoring: Recent advances and research challenges. *RSC Advances*, 5(85):69086–69109, 2015.

[19] S. B. Sulistyo, Siswantoro, A. Margiwiyatno, Masrukhi, A. Mustofa, A. Sudarmaji, R. Ediati, R. Listanti, and H. H. Hidayat. Handheld arduino-based near infrared spectrometer for non-destructive quality evaluation of siamese oranges. *IOP Conference Series: Earth and Environmental Science*, 653(1), 2021.

[20] UNESCO, WHO, and UNEP. *Water Quality Assessments - A Guide to Use of Biota, Sediments and Water in Environmental Monitoring*. F & FN Spon, 2nd ed. edition, 1996.

[21] U. Wanderlingh, C. Branca, and S. Vasi. Portable low-cost autofluorescence analyzer for plankton and plastic detection. In *2021 International Workshop on Metrology for the Sea; Learning to Measure Sea Health Parameters (MetroSea)*, pages 168–172, Reggio Calabria, Italy, 2021. IEEE.