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IOT FOR AGRICULTURAL USE: DEVELOPMENT OF LOW-COST AUTONOMOUS DEVICE FOR REAL-TIME WEATHER MONITORING

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1 ABSTRACT

Water scarcity is one of the main difficulties faced worldwide, and irrigation monitoring can allow efficient use of this vital asset. As a solution for farming monitoring, this study proposed the development of a low-cost sensor module, combining the Internet of Things (IoT) and Long Range (LoRa). The solar-powered and waterproofed prototype monitors air temperature, humidity, and soil moisture. The device presented a low manufacturing cost, reaching savings of up to R$750 ($145) compared to off-the-shelf solutions. To test the prototype, we monitored a point in an irrigated plantation for 30 days. After implementing level alerts for the monitored variables, we observed the data using computers and mobile devices. Despite significant rainfall, the test presented 97% efficiency in radio transmissions with the device at a distance of 163 meters from the gateway. Therefore, demonstrating good resilience to local weather conditions. In conclusion, the device was considered economical, practical, and reliable for field weather monitoring, showing the possibility of using inexpensive IoT in agricultural applications.

Keywords: agriculture 4.0, irrigation management, photovoltaic, smart farm, sustainability.

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2 RESUMO

A escassez hídrica é uma das principais dificuldades enfrentadas mundialmente, e o monitoramento da irrigação pode permitir o uso eficiente desse bem vital. Como solução para monitoramento agrícola, este estudo propôs o desenvolvimento de um módulo sensor de baixo custo, combinando a Internet das Coisas (IoT) e a Long Range (LoRa). O protótipo à prova d'água, alimentado por energia solar, monitora a temperatura e umidade do ar e a umidade do solo. O dispositivo apresentou baixo custo de fabricação, alcançando uma economia de até R$750 ($145) em comparação às soluções disponíveis no mercado. Para testar o protótipo, monitoramos um ponto em uma plantação irrigada por 30 dias. Após a implementação de alertas de nível para as variáveis monitoradas, observamos os dados através de computadores e dispositivos móveis. Mesmo passando por chuvas significativas, o teste apresentou eficiência de 97% nas transmissões de rádio com o aparelho a uma distância de 163 metros do *gateway*. Portanto, demonstrando boa resiliência às condições climáticas locais. Em conclusão, o dispositivo foi considerado econômico, prático e confiável para o monitoramento climático no campo, mostrando a possibilidade de uso de IoT de baixo custo em aplicações agrícolas.

Palavras-chave: agricultura 4.0, gerenciamento da irrigação, fotovoltaico, fazenda inteligente, sustentabilidade.

3 INTRODUCTION

Drinkable water is considered rare worldwide, representing only 1% of terrestrial water, and agriculture uses about 70% of this, therefore being its most significant consumer (FAO, 2020). Thus, irrigation monitoring can be an indispensable step in ensuring the sustainable consumption of this crucial natural resource.

Several studies indicate Internet of Things (IoT) solutions and wireless communication to enable environmental monitoring in rural areas (GANIS *et al.*, 2019). IoT is a concept where smart devices are interconnected to collect and exchange data (ARUN, 2019).

The use of intelligent sensors to increase plantation efficiency characterizes agriculture 4.0. Thus, these sensors must have the ability to transmit data over long distances and low energy consumption (ISLAM; RAY; PASANDIDEH, 2020).

However, commercial sensor modules aimed at monitoring agriculture, such as Waspmote (LIBELIUM, 2021), EM500 SMT (MILESIGHT, 2022), PS5578031 (GLAS DATA, 2022), F8L10ST (FOUR FAITH, 2021), AGRSNNAS923 (ELECOMES, 2020), or ESS5002 (ENVITUS, 2022), have a high cost, usually exceeding the range of R$1,000 ($193). In addition, most of them are manufactured outside Brazil, causing high freight costs and import rates. High implementation costs and lack of access to information make it challenging for small producers to access such systems (BORRERO; ZABALO, 2020).

A conventional solution for field connectivity is mobile telephony, with up to 15 km of range. However, it may have limitations such as lack of coverage, low stability, and costs for network use (GUTIÉRREZ *et al.*, 2013; SENEVIRATNE, 2019). Other options are the Low Power Wide Area Networks (LPWANs), which cover up to 50 km (ARUN, 2019; BORRERO; ZABALO, 2020). Among them, LoRaWAN®, NB-IOT®, and SIGFOX® networks are more widespread in Brazil (RIBEIRO *et al.*, 2020).

Many Low Power Wide Area (LPWA) technologies, among those used in Brazil, are managed by network operators, providing connectivity to users' IoT devices under a packet data contract (Ganis et al., 2019). For example, WND (WND GROUP, 2022) offers Sigfox, and telephony operators such as Claro (CLARO, 2022), TIM (TIM, 2022), and VIVO (VIVO, 2022) trade NB-IoT.

One technology that stands out for allowing its users to create and manage their own LPWAN network is Long Range (LoRa). Brazil can use it in the band from 915 to 928 MHz (THE THINGS NETWORK, 2021). This frequency band, part of ISM bands, is internationally reserved for industrial, scientific, and medical purposes (KHAN, 2019).

The Long Range Wide Area Network (LoRaWAN) protocol refers to a Media Access Layer (MAC) developed by the LoRa Alliance to standardize the use of LoRa technology (KHAN, 2019). Its use was licensed in Brazil in 2017, in ANATEL resolution nº 11542 (ANATEL, 2017).

Private servers are available to access the LoRaWAN network, such as the one provided by the American Tower operator (IOT LABS, 2022). There are also free servers, such as those provided by The Things Network™ (TTN) (THE THINGS NETWORK, 2021).

At the edge of these networks are the end devices, divided between sensor nodes that monitor the process and controller nodes that perform actions on the process. At the center are the gateways, connecting two telecommunication networks with different communication protocols (MEKKI *et al.*, 2019; GANIS *et al.*, 2019; KHAN, 2019).

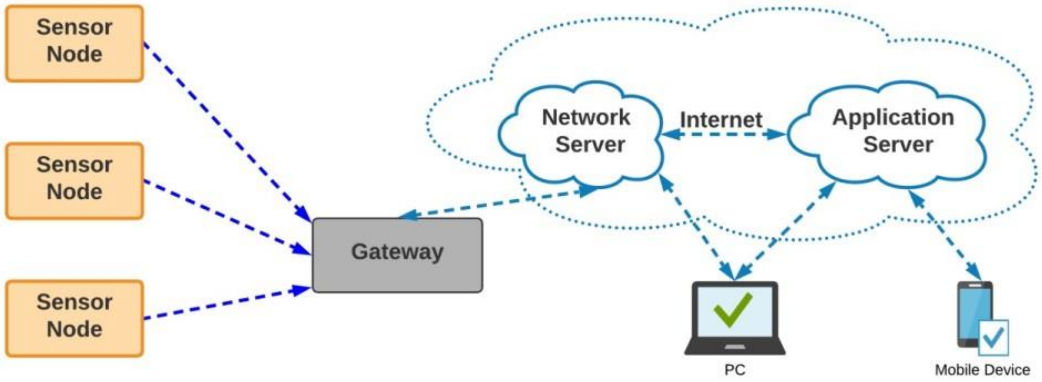
The devices mentioned above can be combined, depending on the characteristics of the monitored or controlled process. They can, in some cases, act only within a local area network (LAN) (BERTO; NAPOLETANO; SAVI, 2021). This way, it is possible to use LoRa technology to offer solutions for rural properties, with or without internet access (GUTIÉRREZ *et al.*, 2013).

Given the demand for low-cost agricultural monitoring solutions, this work aimed to develop and test an open-source, simple-to-implement sensor node appropriate for rural areas. The prototype measures soil moisture, air humidity, and temperature and then saves the data on an internal SD card. Also, the prototype transmits this data wirelessly using LoRa technology to a nearby gateway, which then uploads it over WiFi to open access IoT platforms to be accessed online.

4 MATERIALS AND METHODS

The proposed solution is a LoRa network in the star topology. Figure 1 illustrates the diagram of the proposed network structure; in this configuration, the sensor nodes communicate directly to the gateway, which forwards the information to the Internet.

Figure 1. Diagram of the proposed network structure.



Source: The author (2022)

On what:

Sensor Node: refers to the end device of the network. Equipped with sensors that perform readings of air temperature and humidity, and soil moisture. After that, it transmits them to the gateway through LoRa communication;

Gateway: refers to the central device of the network. It receives data via LoRa and forwards it to an online network server using its WiFi connection;

Network server: refers to The Things Network (TTN) platform, where information is received, processed, and forwarded to the application server;

Application Server: refers to the ThingSpeak™ data integration and analysis platform, responsible for storing and generating graphs, enabling the end user to monitor data over time;

Computer: refers to a device intended for processing large amounts of data, responsible for configuring the gateway and sensor module, as well as registering the devices within the network and application servers;

Mobile Device: refers to a cell phone or tablet device used to view the graphics generated by ThingSpeak, however, visualized from the ThingShow Android application made available by Devinterestdev on the Google Play website.

4.1. Sensor module development

The sensor node components were selected aiming for low-cost yet, energy autonomy and high resilience to adversities found in agricultural environments. Thus, avoiding breaks for maintenance or battery replacement.

After researching and comparing different configurations of assemblies for sensing modules, we analyzed and chose the devices to use in the montage. Table 1 shows the main selected parts, and their prices found both nationally (in Brazil) and internationally (import prices).

Table 1. List of main components for the sensor module montage.

		Domestic Price		Import Price	
Component	**Qty.**	**Unit**	**Total**	**Unit**	**Total**
AHT25 sensor	1	R$ 38.00	R$ 38.00	R$ 11.40	R$ 11.40
Ethernet cable (meter)	4	R$ 1.00	R$ 4.00	R$ 1.00	R$ 4.00
TH75 waterproof sensor case	1	R$ 30.00	R$ 30.00	R$ 5.90	R$ 5.90
HW-390 sensor	1	R$ 21.00	R$ 21.00	R$ 10.00	R$ 10.00
MOSFET Shield D4184	1	R$ 14.00	R$ 14.00	R$ 9.00	R$ 9.00
Battery Holder 18650	1	R$ 7.56	R$ 7.56	R$ 2.07	R$ 2.07
Li-ion Battery 18650 2600mAh	1	R$ 40.00	R$ 40.00	R$ 40.00	R$ 40.00
Solar panel 5v 200mA	1	R$ 15.41	R$ 15.41	R$ 9.75	R$ 9.75
Connector JST PH 2P 2.00mm	4	R$ 2.50	R$ 10.00	R$ 0.71	R$ 2.85
Charger Board CN3065	1	R$ 23.49	R$ 23.49	R$ 14.09	R$ 14.09
2P on/off push button switch	1	R$ 1.99	R$ 1.99	R$ 1.11	R$ 1.11
2P push button self-reset switch	1	R$ 1.81	R$ 1.81	R$ 1.24	R$ 1.24
RFM95W transceiver	1	R$ 35.00	R$ 35.00	R$ 20.90	R$ 20.90
Breakout board for ESP 7-12	1	R$ 7.83	R$ 7.83	R$ 0.92	R$ 0.92
915MHz 2.15Dbi Helical Antenna	1	R$ 4.00	R$ 4.00	R$ 6.00	R$ 6.00
ESP8266 WeMos D1 mini	1	R$ 24.90	R$ 24.90	R$ 10.52	R$ 10.52
WeMos RTC and micro SD shield	1	R$ 15.37	R$ 15.37	R$ 10.03	R$ 10.03
WeMos battery shield	1	R$ 38.30	R$ 38.30	R$ 10.00	R$ 10.00
CR1220 battery	1	R$ 0.80	R$ 0.80	R$ 0.80	R$ 0.80
WeMos Tripler Base	2	R$ 22.50	R$ 45.00	R$ 4.87	R$ 9.74
Micro SD card (2-32GB)	1	R$ 14.90	R$ 14.90	R$ 10.03	R$ 10.03
IP65 plastic enclosure 158x90x60mm	1	R$ 72.48	R$ 72.48	R$ 40.07	R$ 40.07
PG9 cable gland IP68	2	R$ 8.10	R$ 16.20	R$ 2.09	R$ 4.17
Totals	30		R$ 482.04 ($ 93.18)		R$ 234.59 ($ 45.35)

Source: The author (2022)

Aside from the main parts, we also acquired parts of lesser value, commonly known as "miscellaneous". To maximize cost savings, we bought these parts in kits. Table 2 shows a list of these miscellaneous parts, along with their corresponding prices, both domestically (in Brazil) and internationally (import prices).

Table 2. List of miscellaneous for the sensor module montage.

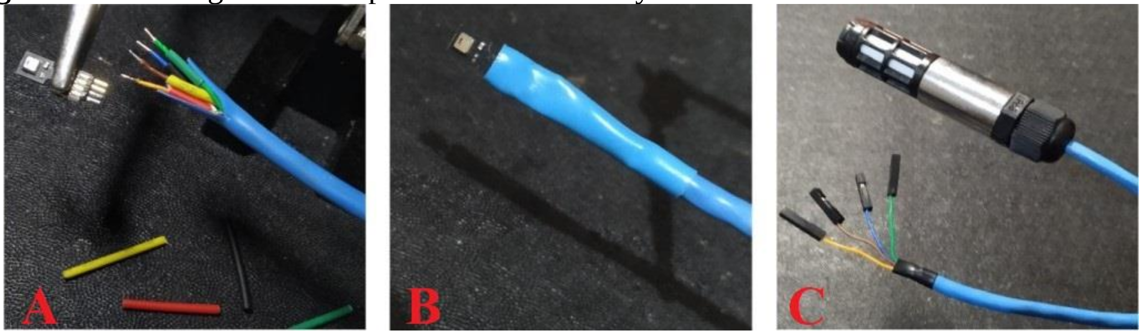
Component		Domestic Price		Import Price	
	Qty.	**Unit**	**Total**	**Unit**	**Total**
Resistor 10k	2	R$ 0.08	R$ 0.15	R$ 0.02	R$ 0.04
Dupont Connector 1x1P 2.54mm	9	R$ 0.03	R$ 0.27	R$ 0.13	R$ 1.17
Dupont male pin 22-28AWG	5	R$ 0.03	R$ 0.15	R$ 0.13	R$ 0.65
Dupont female pin 22-28AWG	4	R$ 0.03	R$ 0.12	R$ 0.13	R$ 0.52
Heat shrink tubes (1-14mm)	1	R$ 0.58	R$ 0.58	R$ 0.30	R$ 0.30
DIODE 1N5819	2	R$ 0.20	R$ 0.40	R$ 0.07	R$ 0.15
M3 spacers 2x10mm, 6x12mm and 2x15mm	10	R$ 0.36	R$ 3.61	R$ 0.15	R$ 1.54
7 M3 nuts and 3 M3 screws	10	R$ 0.36	R$ 3.61	R$ 0.15	R$ 1.54
Totals	43		R$ 8.89 ($ 1.72)		R$ 5.92 ($ 1.14)

Source: The author (2022)

We divided the construction of the sensor node into three parts; firstly, we built the sensor circuits. Afterward, we assembled the radio module and fitted it with the other shields inside a waterproof enclosure.

AHT25 sensor circuit: It performs air temperature and humidity measurements through the AHT25 sensor from Aosong. We chose it for its low cost, low power consumption, and "probe-like" design that allows us to position it, with an extension cable, close to the data collection point. For this, we soldered the sensor terminals to a 1.5-meter network cable and shielded it with heat shrink tubing. After that, we protected the sensor with a TH75 waterproof case. Thus the sensor can be used outdoors, protected from direct contact with solar radiation, rain, and dust (AOSONG, 2021). Figure 2 illustrates the preparation of the AHT25 sensor.

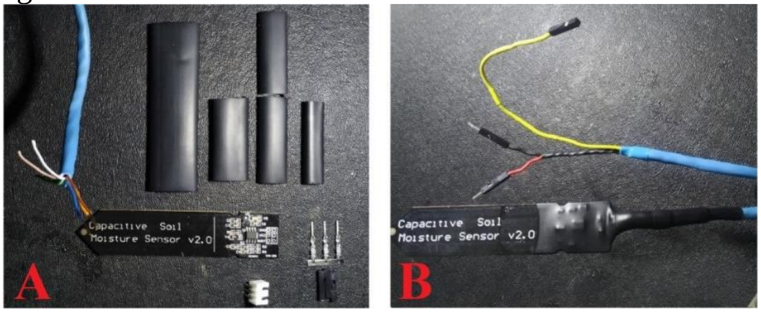
Figure 2. Mounting the air temperature and humidity sensor.



Where: A) step 1; B) step 2; C) step 3.
Source: The author (2022)

HW390 sensor circuit: Monitors soil moisture from the HW390 capacitive sensor (Figure 5-B1), communicating with the microcontroller through an analog signal from 0 to 3.3V. We chose this model because of its high calibration replicability, high accuracy after calibration, and low cost in the national market (COSTA, 2020). A limitation in the use of this sensor is its communication cable of only 20 cm, which we replaced with a network cable of 2.5 meters. Another limitation is the exposure of electronic components in its upper section, which we protected with heat-shrink tubes. The work of Micromet (2021) indicates a similar adaptation. Figure 3 shows the suitability of the HW390 sensor.

Figure 3. Mounting the soil moisture sensor.



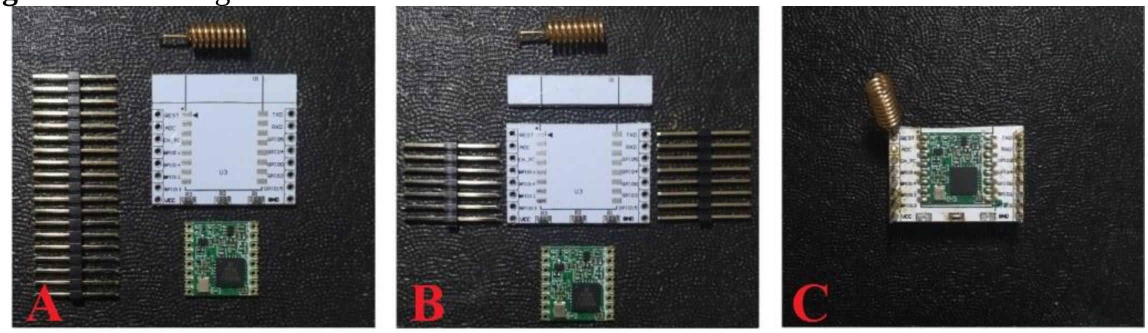
Where: A) step 1; B) step 2.
Source: The author (2022)

Another point to consider was that the HW-390 consumes a current of 5 mA, even during the microcontroller's deep sleep mode (DFROBOT, 2017). To reduce this overhead, we used the Xy-mos Dual D4184 MOSFET shield, which acts as a power switch for the HW-390 sensor. Thus, the sensor consumes power for only 150 milliseconds to take readings.

Power and control circuit: Composed of a 5V 200 mA Polycrystalline Solar Panel that powers the microcontroller and a CN3065 charger shield that manages the charging of a 2600mAh SONY VTC5A 18650 Lithium Battery. A PBS-11A 2P Button (with lock) performs the "On-Off" command, while a PBS-11B 2P Button (with auto-reset) accomplishes the "Reset" command.

Radio circuit: The module RFM95W from the manufacturer Hoperf performs the LoRa communication, communicating with the microcontroller through the SPI protocol. We selected it because it is easily found in the national market, carrying out LoRa transmissions in the 868 MHz (European standard) or 915 MHz (Brazilian standard) frequency bands (HOPERF, 2019). A limiting point in using the RFM95W is its compact construction with a 2.00 mm pin spacing. For its use with PCBs or breadboards, we used the solution presented in Paredes-Parra et al. (2019) with a mounting shield for ESP 7-12 adapting the RFM95W outputs to 2.54mm spacing. Figure 4 shows the RFM95W adjustment procedure.

Figure 4. Mounting the radio shield for the sensor module.



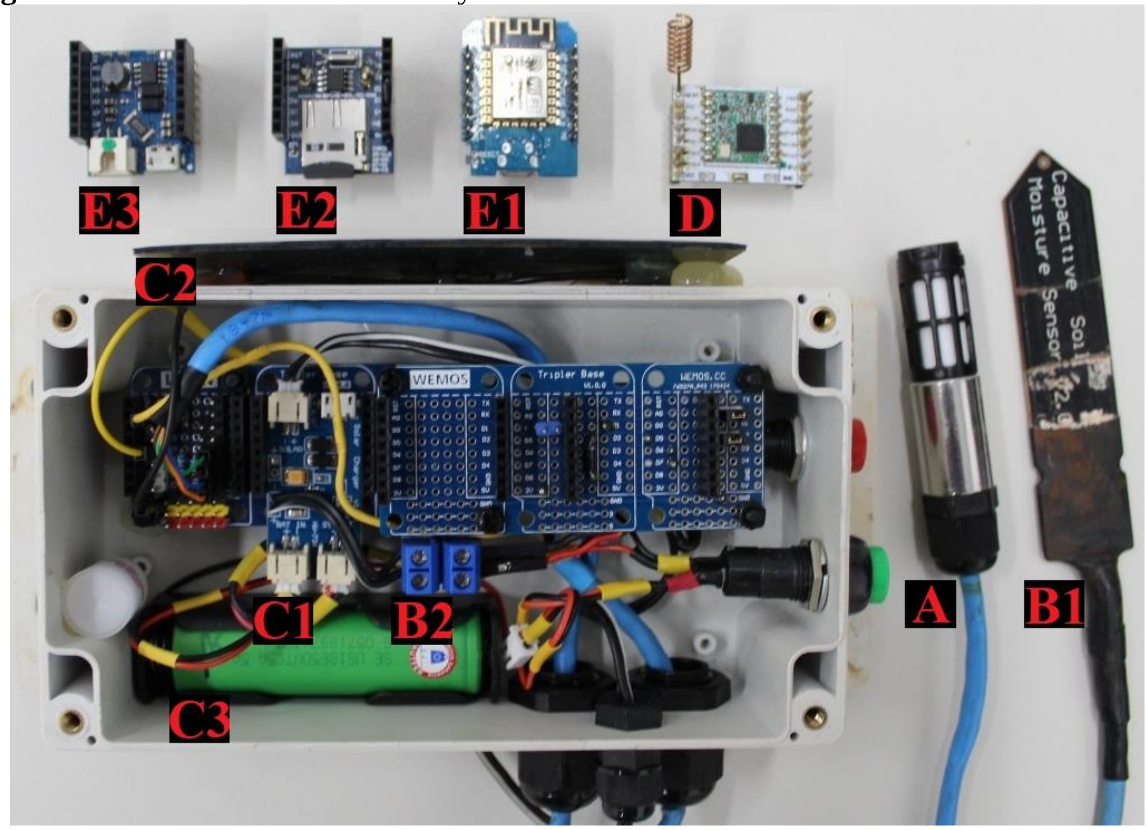
Where: A) step 1; B) step 2; C) step 3.
Source: The author (2022)

WeMos D1 mini circuit: Composed of three WeMos shields, these being: The ESP8266 microcontroller unit (MCU), which performs both hardware and software management; the "RTC and micro SD" Shield generates an internal clock and saves data into a micro SD card; and a Battery Shield, which receives the voltage from the Power Supply Circuit and adapts it to power the MCU. Input voltage levels can range from 3.3V to 4.2V; even with voltage fluctuations at the input, the output remains at 5V.

To connect the components described above, we use two Wemos Triplicator Bases, which are also fixed via two 1x8 2.54mm stackable female pin bars. So, in addition to joining the standard WeMos shields, we fit the sensor terminals and the MOSFET D4184, Charger CN3065, and RFM95W shields. This way, the components can be attached and detached without soldering needed.

Finally, we fixed the set, with hot glue, inside an IP65 Waterproof Plastic Box. Figure 5 shows the result of the sensor module assembly (without the acrylic cover).

Figure 5. The sensor module assembly



Where: A) AHT25 Sensor Circuit; B1) HW390 Sensor Circuit; B2) MOSFET Shield D4184; C1) Charger Board CN3065; C2) Solar panel 5v 200mA; C3) Li-ion Battery 18650 2600mAh; D) Radio Circuit; E1) ESP8266 WeMos D1 mini; E2) WeMos RTC and micro SD shield; E3) WeMos battery shield.
Source: The author (2022)

The sensor node was programmed based on the Arduino-LMIC library, available on the GitHub (https://github.com/mcci-catena/arduino-lmic) platform. This library was developed for the Arduino IDE software that uses the C++ programming language.

The program starts importing the libraries when the device is turned on. The MCU input/output pins are mapped, and software variables are declared. The communication protocols of the shields, sensors, and radios are configured and started. Next, the program starts the “void setup” routine, starting the Watchdog function counting. This process is performed independently of the main code flow. If the code crashes, Watchdog causes a software reset on the MCU.

In the sensing phase, the MOSFET D4184 powers the HW390 sensor. While it configures, the microcontroller takes the AHT25 sensor readings. The MCU then proceeds with the measurements of the HW390. After that, the MOSFET shield cut off the HW390 power.

Then, the module performs the data-sending phase; in this process, the sensor node can save the information on a microSD card and send it via LoRa and WiFi (in parallel). For field testing, sending via WiFi was disabled; considering the sensing site (agricultural area), this network would have no range.

After sending the information, the MCU stops the Watchdog counting and enters deep sleep mode, considerably reducing the module's consumption. The microcontroller remains asleep for 15 minutes. At the end of the deep sleep time, the MCU restarts and reconfigures itself for another cycle of readings; however, at the time of sending information via LoRa radio, the count of Uplinks (messages to the network server) is continued through a counter stored in the ESP8266's RTC memory.

4.2. Gateway development

For the sensor node test, we built a gateway based on the design of Seneviratne (2019). In his book, the author details the development of a single-channel gateway using a Raspberry Pi 3B and a mounting shield for the RFM95W transceiver from the manufacturer Adafruit.

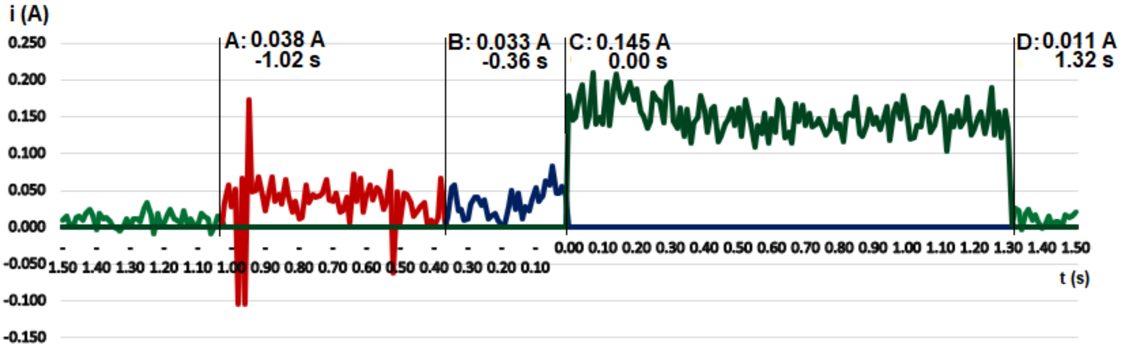
5 RESULTS AND DISCUSSION

5.1. Power consumption test

To obtain the energy consumption of the sensor node and the maximum time of its operation without solar incidence, we performed four measurements of the Potential Difference (PD) using an oscilloscope Tektronix model TDS1002B. To find the current consumed, we used the concept of Ohm's First Law (BOYLESTAD; NASCIMENTO, 2004) and set up a circuit with a resistance of 1 Ohm to correlate the voltage at its poles with the supply current of the sensor node, connected in parallel.

The oscilloscope generated a report of the measurements in CSV (comma-separated values) format. Figure 6 presents an excerpt of the graph prepared from these data, encompassing the active phase of the sensor node.

Figure 6. Average current vs. time during sensor module operation.



Where: A) Is the start of the analog sensor readings; B) Is the start of the I2C digital sensor readings; C) It is the beginning of the LoRa transmission; D) It is the beginning of deep sleep mode.
Source: The author (2022)

The analog sensor readings (adc) occur between A) and B); the I2C digital sensor readings (i2c) occur from B) to C); the LoRa transmission phase (LoRa) occurs from C) to D); and the deep sleep mode (sleep) occurs from D) to A). By using Equation 1, the average electric current consumption (I average) of the sensor node was calculated based on the current consumption "I" (in amperes, A) and the duration "T" (in seconds) of each operational phase.

$$I\ average = \frac{I(sleep)*T(sleep) + I(adc)*T(adc) + I(i2c)*T(i2c) + I(LoRa)*T(LoRa)}{T(sleep) + T(adc) + T(i2c) + T(LoRa)} \quad (1)$$

Considering a deep-sleep time of 15 minutes, we have:

$$I\ average(15) = \frac{11*(15*60) + 37*0.66 + 33*0.36 + 143*1.32}{(15*60) + 0.66 + 0.36 + 1.32} = 11{,}22\ mA \qquad (2)$$

Once we obtain the average current consumption and know the battery capacity, we use Equation 3 to calculate the battery lifetime "D" (in days):

$$D = \frac{Battery\ (mAh)}{I\ average} = \frac{2600\ (mAh)}{11{,}22} = 231{,}73\ h \qquad (3)$$

Under these conditions, the sensor node offers an autonomy of up to 9 days, 15 hours, and 43 minutes without sunlight. Considering that it has an average consumption of 11.22 mA, using Equation 3, we can estimate that the night-time consumption (in 12 hours) is close to 135 mAh—a charge that, with intense sunlight, the solar panel can replenish in about 41 minutes.

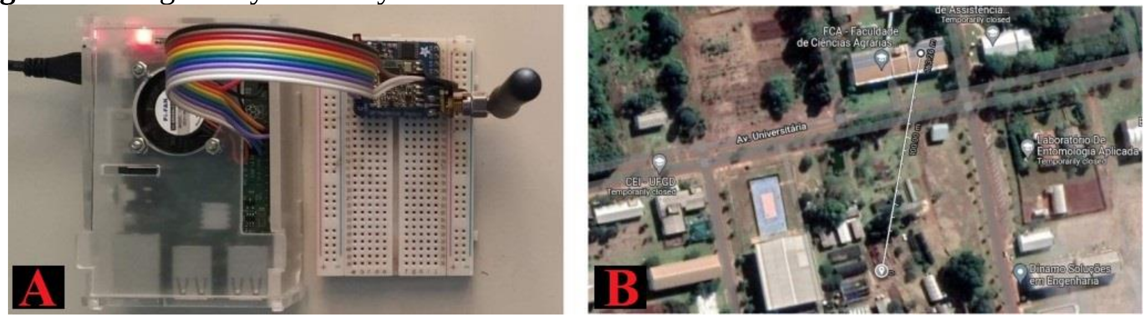
Considering that the maximum current of 145 mA consumed by the device for 1.32 seconds is less than the solar panel capacity of 200mA, during daylight, the photovoltaic circuit should be able to disconnect the battery and power the sensor module.

5.2. Field test

For prototype validation, we monitored a cut flower plantation of the gladiolus species, popularly known as Palma de Santa Rita, for 30 days in June 2022. The cultivation was in the Faculty of Agricultural Sciences (FCA) gardening area of the Federal University of Grande Dourados (UFGD), at the coordinates of 22º 11' S and 54º 56' W, with an altitude of 446 m. We selected this location to expose the prototype to the local cultivating conditions and share the collected data with the academic cultivators.

First, we installed the gateway in the FCA building, where a connection to the WiFi was possible. Figure 7 shows the gateway and its localization, 163.26 meters from the monitored site.

Figure 7. The gateway assembly and location.

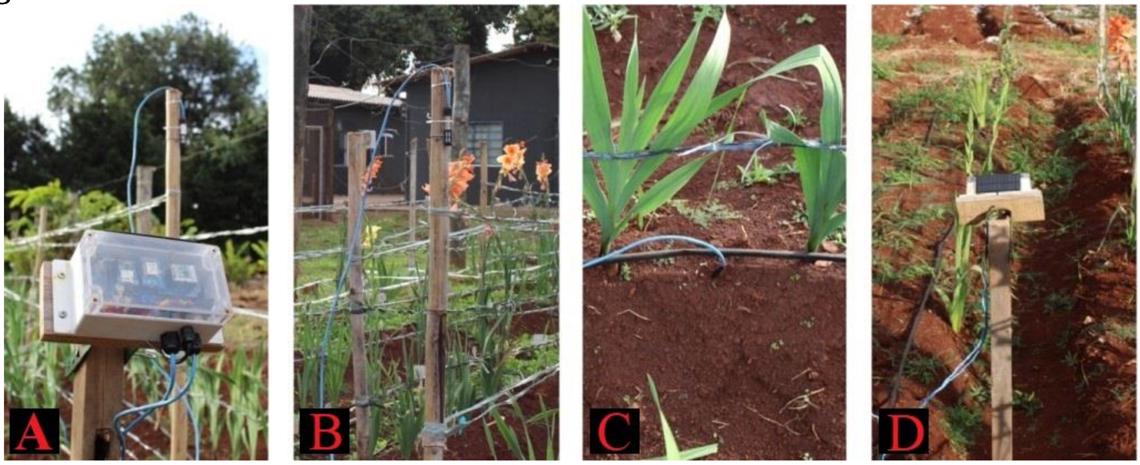


Where: A) Is the gateway assembly; B) Is the gateway location.
Source: The author (2022)

Second, we mounted the sensor node at a height of 1.1 meters. Then we positioned the humidity and air temperature sensor at 1.4 meters. We also inserted the soil moisture sensor into the ground between two Gladiolus at a depth of 10 cm. Finally, we directed the solar panel north at

70° concerning the vertical line. Figure 8 shows the assembly of the assembly.

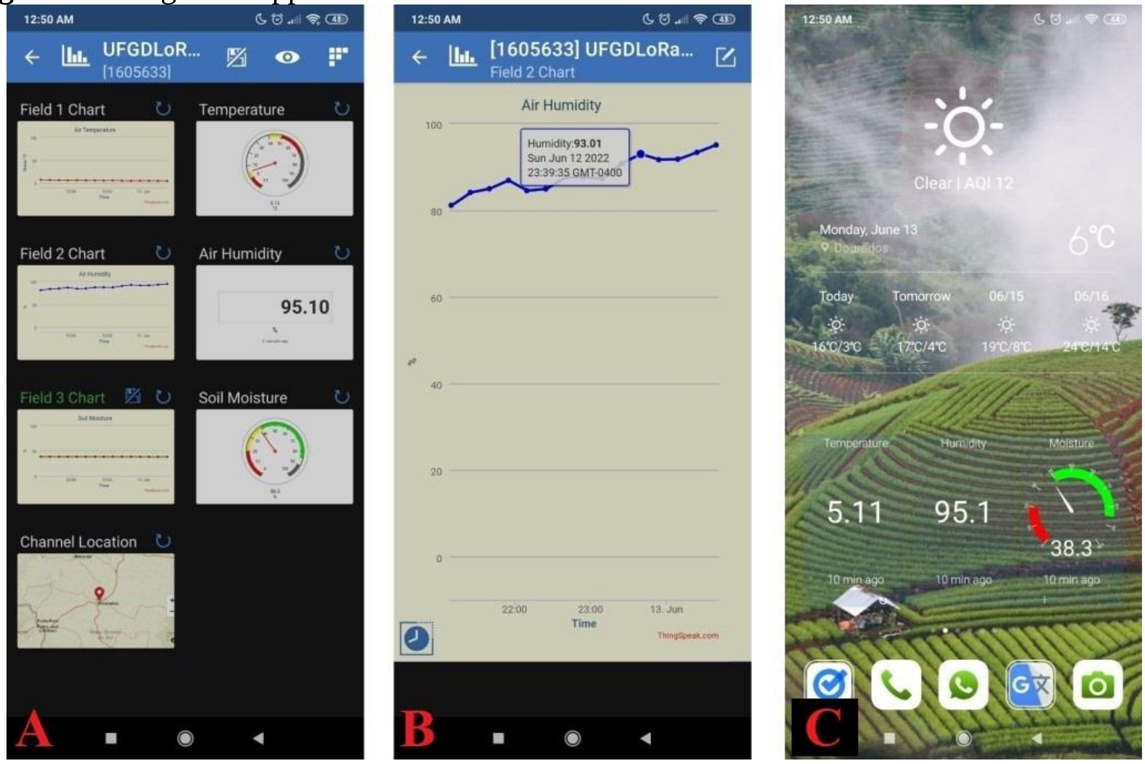
Figure 8. Sensor module test scenario.



Where: A) Is the module assembly; B) Demonstrates the positioning of the humidity and air temperature sensor; C) Is the positioning of the soil moisture sensor; D) Shows the direction of the solar panel.
Source: The author (2022)

During the operation, using web browsers, we graphically visualized the data on the ThingSpeak platform. We also tracked measurements and managed alert set points on mobile devices with the ThingShow app, a procedure demonstrated in Figure 9.

Figure 9. ThingShow application.

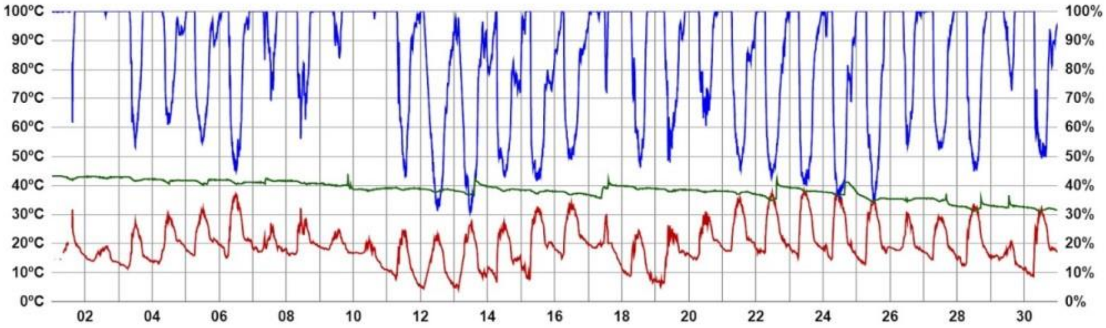


Where: A) Is the main dashboard; B) Demonstrates the air humidity graph; C) Shows the data widget.
Source: The author (2022)

The platforms allowed stakeholders such as teachers, students, and researchers to collect data for their use cases.

ThingSpeak stores, in its free version, up to 3,000 messages per year in CSV format. Thus, it was possible to export these data for future analysis and generate a graph using the Google Sheets application, as shown in Figure 10.

Figure 10. Graph of air temperature (in red), relative humidity (in blue), and soil moisture (in green).



Source: The author (2022)

According to the Guia Clima website (www.clima.cpao.embrapa.br), the local weather station recorded rainfall of 38.4 mm on 09/06 and 8.5 mm on 17/06. From the collected data, we could observe that the sensor node detected these rains.

The sensor module backed up all readings to an internal micro SD card, ensuring readings taken during transmission failure or gateway issues are saved.

When comparing the messages transferred via radio with those saved on the microSD card, we could observe that node successfully delivered 97.94% of the information to the online application. Thus, we can say that the observed weather conditions did not significantly affect the sensor node's functioning.

6 CONCLUSION

The laboratory tests showed that the photovoltaic power supply was an excellent alternative to ensure the continuous operation of the proposed sensor module.

Field tests revealed a resilience appropriate to use in rural areas.

Its manufacturing cost was considered low compared to other devices found on the market.

The digital platforms ThingSpeak and ThingShow used proved to be practical and versatile for the monitoring and analysis of data collection.

Despite the obstacles between the sensor node and the gateway, the system showed high efficiency in radio frequency data transmission.

In future work, range tests can be performed to calculate the maximum area covered. In this regard, different antenna types and repeater nodes can be evaluated.

In summary, the developed device is economical, practical, and reliable for remote weather monitoring. With a large amount of data collected and alarms of high/low air temperature, humidity, or soil water content. It can be a tool to enable conscious water consumption in irrigation and guide new remote IoT solutions with limitations to internet access via conventional means.

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