IoT Sensing Box to Support Small-Scale Farming in Africa

Antonio Oliveira-Jr[1,2](✉), Carlos Resende[1], André Pereira[1], Pedro Madureira[1], João Gonçalves[1], Ruben Moutinho[1], Filipe Soares[1], and Waldir Moreira[1]

[1] Fraunhofer Portugal AICOS, 4200-135 Porto, Portugal
{antonio.junior,carlos.resende,andre.pereira,pedro.madureira, joao.goncalves,ruben.moutinho,filipe.soares,waldir.junior}@fraunhofer.pt

[2] Institute of Informatics (INF) - Federal University of Goiás (UFG), Goiânia-GO 74690-900, Brazil
antoniojr@ufg.br

Abstract. Small-scale farming has an important role in agriculture. Driven by the popularization of the Internet of things (IoT), this paper presents an IoT sensing box prototype coupled with soil analysis through computer vision to help small-scale farmer improve their yields. The idea of combining image-based soil classification with regular soil sensors is to improve the reliability of the sensed data, by minimizing the occurrence of incorrect estimates for specific soil types. The prototype follows a Do-It-Yourself (DIY) approach, and is based on commercial off-the-shelf (COTS) hardware and open source software. Additionally, the prototype includes a casing to house all the hardware which was designed considering standard 3D printing to be easily replicated. As the presented solution is currently on a prototype stage, the validations carried out in a controlled, in-lab environment include guaranteeing the proper process for image acquisition and data quality of the computer vision component (images collected from sensor camera, and their quality), suitable data exchange over the sockets, and the sensing box's ability to gather data.

Keywords: Internet of Things · Sensing box · Computer vision · Soil analysis · Small-scale farmers · Rural Africa

1 Introduction

One can see the impact and importance of Information and communication technology (ICT) for agriculture given the incentives for rural digital transformation and market value of digital farming for upcoming years [9,11]. Given the importance of the small-scale farming for food production worldwide [10,18], it makes sense to also provide access to ICT solutions for the small producers.

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Moreover, IoT adoption in Africa is of interest for while now [14,15,17] and even with its still low penetration, one can find different efforts to provide access to ICT, for instance, Gichamba et al. [16], Sousa et al. [24] and Oliveira et al. [19] focus on the provision of mobile aplications and communication infrastructure to reduce digital divide and improve the quality of life of people in rural areas of Kenya and Mozambique.

Motivated by that, we have proposed an IoT sensing platform [20,21] to popularize digital farming in rural Africa, helping farmers better understand their soil condition. Following this work, this paper presents the IoT sensing box development which is composed of sensors that provide pH, moisture, air temperature, and light readings. These readings are to keep small farmers and soil experts aware of the soil current status. The IoT sensing box also includes an image acquisition module for computer vision-based soil classification related with texture and colour information.

The sensing box component follows a Do-It-Yourself (DIY), and integrates single-board computer, microcontroller, sensors, Wi-Fi communication module, LEDs and LED driver with extensible software that implements sensor reading modules, and communication sockets (for data exchange and sensor configuration). The hardware and software architectures of the sensing box not only ease further developments on top of the solution, but also facilitate the assembly of the solution based on hardware easily found in local markets.

Moreover, the IoT sensing box presents the design details of the casing proposed to accommodate all its hardware (i.e., sensors, micro-controller, SBC, illumination, mounting parts). The casing was thought to allow ease assembly of the components as well as providing protection while the solution is being used for data collection or being transported. Additionally, the design considered standard 3D printing dimensions, so the casing can be easily printed and replicated elsewhere.

It is worth mentioning that the proposed IoT sensing box integrates the Project AFRICA [22] that aims at developing a green-energy driven technology solution to support the on-site, cost-affordable fertiliser production to small-scale farmers in Africa.

In order to provide a better understanding of the proposed IoT sensing box, this paper is organized as follow. Section 2 details the IoT sensing box architecture focusing on the considered hardware. Then, Sect. 3 goes through the image acquisition setup needed for the computer vision-based soil analysis. Section 4 summarizes the casing design and assembly based on specific requirements, while Sect. 5 describes the final IoT sensing box prototype and software architecture. Section 6 concludes the paper.

2 IoT Sensing Box Architecture

The actual version of the IoT sensing box considers the Wi-Fi interface to function as an access point to which the user equipment (e.g., smartphone, tablet, laptop) connects serving as relay to send the data to the backend server. It is important to mention that the IoT sensing box is built in modular way to allow the inclusion of other wireless communications technologies (such as LoRa, BLE) as well as other sensors and probes. Figure 1 presents the hardware architecture of the IoT sensing box, showcasing its sensors, interfaces, and radio communication.

As the IoT sensing box is meant to be easy replicated, we followed a DIY approach considering components that i) can be easily found in local markets; and ii) can be easily connected without the hardware complex tasks. The hardware architecture can be seen as having three main parts as follows.

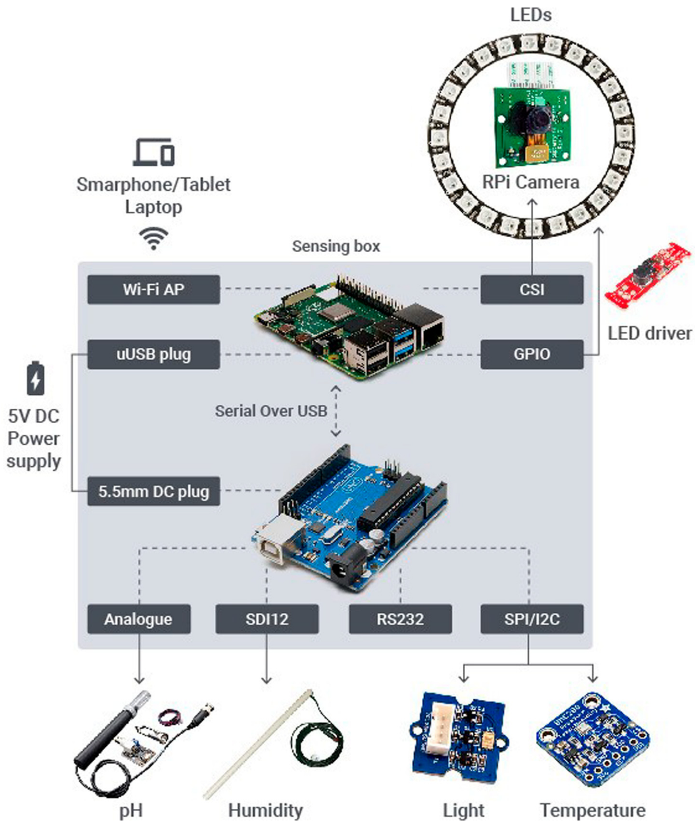


Fig. 1. Sensing box hardware architecture.

Single-Board Computers (SBC) - The IoT sensing box has two SBCs, a Raspberry Pi which is the brain of the solution, and an Arduino that interfaces with all soil and environment sensors. Our choice for these SBCs come from project AFRICA's requirement for considering low-cost, off-the-shelf hardware. Both SBCs are regularly used in DIY projects as they are cheap and with enough features to allow fast development and prototyping as desired by the project's consortium.

Moreover, the Raspberry Pi has been chosen as it offers i) a built-in Wi-Fi communication interface that can be configured in access point (AP) mode, and through which the User Equipment (UE) will connect to get sensor data; and ii) an interface with the camera module through its Camera Serial Interface (CSI) port using a ribbon cable, and control the LED driver activation through its General-Purpose Input/Output) GPIO interface for the image acquisition process.

It is important to mention that the use of Wi-Fi is also a project requirement since the sensing box is to provide a communication means over this wireless technology. This also explains why we have not considered other technologies such as Global System for Mobile Communications (GSM) or Low Power Wide Area Network (LPWAN), as the box is meant to connect to another device (i.e., smartphone) and not a network.

The Arduino, through a header with screw connectors and protoboard space [1], offer different interfaces, such as SDI12, SPI/I2C, RS232 and analogue. The reason we considered Arduino as interface to sensors is due to i) lack of support to SDI12 protocol by the Raspberry Pi [12]; and ii) Arduino allows a low-level control of the microcontroller, its timers and interrupts. The interface between the Raspberry Pi and Arduino uses a common USB cable through serial communication.

It is worth noting that, as our work is at a prototype stage, we are not interested in the performance of Arduino (e.g., handling concurrent sensors) and RPi (e.g., energy efficiency). Instead, we are more interested in understanding whether they are capable of helping us building a sensing box that is cheap and easy to implement following a DIY approach. A more complete set of validation tests and results are yet to be realized through experiments in near future as project AFRICA advances.

Sensors - Different sensors are used in the IoT sensing box to measure pH, moisture, air temperature and light, and also to capture images of the soil. These sensors are cheap, easy to find and are based on well-known interfaces (i.e., SDI12, SPI/I2C, RS232 and analogue).

The pH sensor for semisolid material with an analogue interface is a DFRobot SEN0249 [4]. It is connected to the Arduino through the screw connectors on the Arduino header.

We also use a multi-depth industrial grade soil monitoring probe that communicates through SDI. This is the Sentek drill & drop soil moisture, salinity and temperature probe [7]. If cost or market availability may be an issue, a low-cost alternative should be a Seeed studio 314010012 moisture and temperature sensor [8].

An Adafruit 2652 BME280 I2C/SPI temperature sensor [2] is connected to the sensing box by soldering its pins into the protoboard space of the Arduino header.

The SeeedStudio (101020030) digital light sensor [6] is connected through the I2C interface available in the sensing box (Arduino header).

The Pi NoIR Camera V2 [5], capable of 1080p video and still images, connects to Raspberry Pi through CSI port.

Power Supply - In order to power all the hardware present in the IoT sensing box, we considered the situation when access to power grid is available, or the use of alternative supply in the case remote sensing is being done.

A 5V DC power supply is considered to feed the system. Such supply can be composed of standard AC/DC power adaptors that are compatible with Raspberry Pi and Arduino, or a power bank compatible with Arduino and Raspberry Pi requirements.

3 Image Acquisition Module for Computer Vision

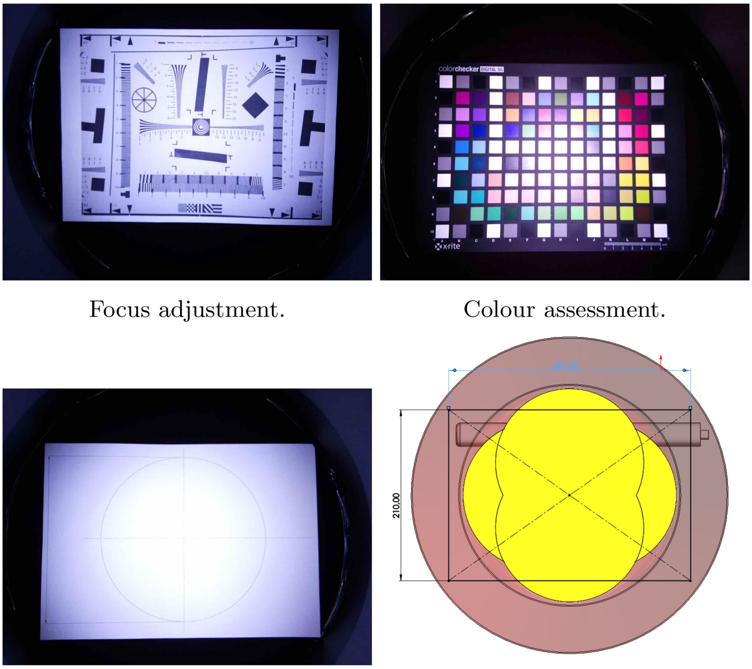
Capacitance sensors have long been suspected of sensitivity to variations in temperature. This can be corrected if the soil type or soil texture are known. Dalton et al. [13] found that correction protocols have improved the variation of water content, previously overestimated due to diurnal fluctuation only. Therefore, we raised the hypothesis of using computer vision to classify the type of soil so that it can be later crossed with the remaining data of the sensor probes, in multiple soils to be tested in the future.

The computer vision component [21] classifies soils according to the Food and Agriculture Organization (FAO) World Reference Base soil groups (WRB), and USDA Soil Taxonomy suborders [25]. Deep Learning [23] approaches have recently had a great impact in image analysis. Due to the large variability of soil characteristics in the world, in [21] we have studied machine learning approaches with Convolutional Neural Networks to the context of soil images. In the current IoT sensing platform it is envisioned that 2D images of the soil are collected together with the other sensor readings in the same locations.

In order to work properly, the camera and light system that integrate the image acquisition module were calibrated to provide high image quality for the computer vision-based soil classification to work properly. The following main tasks were performed to allow the IoT sensing box prototype to satisfactorily capture high quality soil images.

Focus Adjustment: We started the calibration process by evaluating the sharpness variation while manually adjusting the camera focus to around 30 cm. The target used was a printed version of the ISO 12233:2000 test chart, over a light absorbing black-out material. The actual distance between the camera and the target is 33 cm, but we must leave some tolerance because soil matter can be irregular after mixing. The photo in Fig. 2a was obtained directly from the camera without post-processing. We could observe that the edge-to-edge sharpness is not totally constant, however this is not an issue as some irregularity of the soil is also expected in real world.

Colour Assessment and Camera Parameters Adjustment: Figure 2b shows a capture of a real ColorChecker® Digital SG by x-rite [3], covering a good range of colour space. To avoid hotspots, the ISO and shutter speed of the



Focus adjustment. Colour assessment.

Uniformity of light in practice. Uniformity of light in theory.

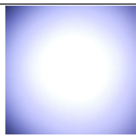
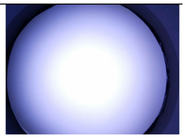
Fig. 2. Camera and light calibration.

camera had to be adjusted. ISO went down to 100 to preserve detail and reduce noise as much as possible, and the shutter was set to 1/30 s. Due to the weight of the whole IoT sensing box, the camera should not shake and create motion blur in normal wind speeds in the crop fields. This can be confirmed in field tests and some fixes are possible.

Centrality and Uniformity of Light: To measure the area covered by the illumination system, a target composed by a A4 paper with a circle corresponding to the real diameter (180 mm) of the sensing box was used to make the photo in Fig. 2c. Our soil classifier only requires squared images, so the goal was to obtain a 200 $\times$ 200 mm image with uniform light. By comparing Fig. 2c with Fig. 2d where the dimensions of the A4 rectangle (297 $\times$ 210 mm) are shown, it can be observed that the theoretical FOV of the LED set was mostly achieved.

Region Selection Based on Entropy Levels: It is of utmost importance that the square region selected contains homogeneous levels of pixel intensity. To assess that, entropy levels were calculated for different crops sizes in the LUV colour space. L stands for luminance, whereas U and V represent chromaticity values of colour images. According to Table 1, 0.94 of entropy is reached with image crops below 87%. In this case, an image up to 1700 $\times$ 1700 pixels can be taken and delivered to the artificial intelligence model that classifies the type of soil.

Table 1. Entropy measurements.

			
Histogram Entropy Luminance	0.09	0.94	1.00
Histogram Entropy U	0.06	0.29	0.32
Histogram Entropy V	0.09	0.17	0.20

4 Casing Design and Assembly

The protective casing for the IoT sensing box was designed in order to prevent moisture and dust from reaching the hardware, robust outdoor use, compact, easy assembly (i.e., few elements, large parts, simple mounting), based on locally available resources, easy usability, safe transport and simple maintenance.

As presented in Fig. 3, to provide a better handling of the IoT sensing box, the sensing box casing includes a handle element (1 and 2) to allow for easy to transport as well as quick assembly into the cabinet. Different spaces are moulded with the shape of the electronic components to allow assembly through the upper part of the casing (3). One side of the casing (4) exhibits all the input and output interfaces of the sensing box, allowing quick access without mounting or dismounting the casing. Between the cabinet and sensing box, there is a small thin layer of foam (5) to absorb shocks and minimize the entry of dust and moisture.

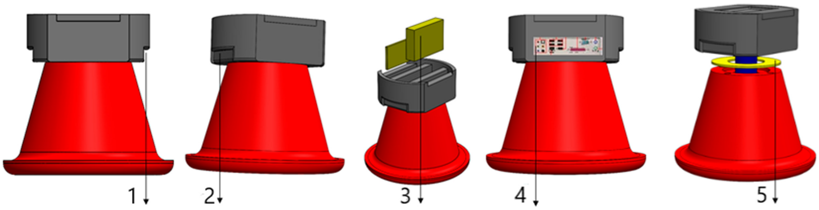


Fig. 3. Detailed view of the casing: 1,2) Sensing box handles; 3) Electronic components; 4) Input and output interfaces; 5) Foam shock-absorption.

The exposed elements are built with edges and grooves so that, when the pieces are put together, there is an extra layer of protection between the electronic components. This concept looks at the case from three relevant perspectives, namely protection, simplicity and usability, in order to guarantee proper shelting of the inner components of the proposed IoT sensing box, and allows its easy replication anywhere else in the world.

Figure 4 highlights all external components, along with the areas that the user may or not interact or block. The design focuses on resulting casing that provides an intuitive and natural interaction with the user. The buttons, sensors and interfaces are appropriately identified and resort to different interruption symbols and information that indicate where the user should not place objects or interact (i.e., to refrain from blocking the light sensor).

The design has slots to facilitate the accommodation of the humidity and pH probes so that they seamless integrate into the IoT sensing box when it is being transported or not used. The position of the slots took into account the internal space to ensure the proper positioning of all parts, to result on a robust structure, and to provide all mechanical properties for intense outdoor use and shock absorption.

5 IoT Sensing Box Prototype

Initial validations have shown that the sensing box and the cabinet interact perfectly. The fitting between them, made by the union of the end of the sensing box with the concavity of the cabinet, results in a quick adjustment and alignment and easy to process in any situation. Figure 5 shows the outside view of the sensing box prototype and the cabinet responsible for blocking the external

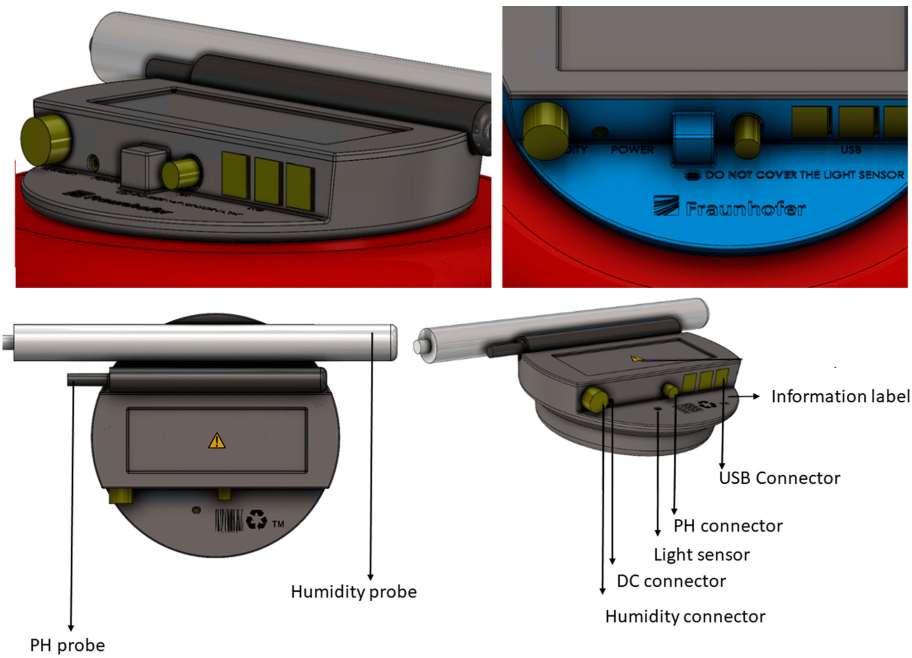


Fig. 4. Sensing box - exterior components.

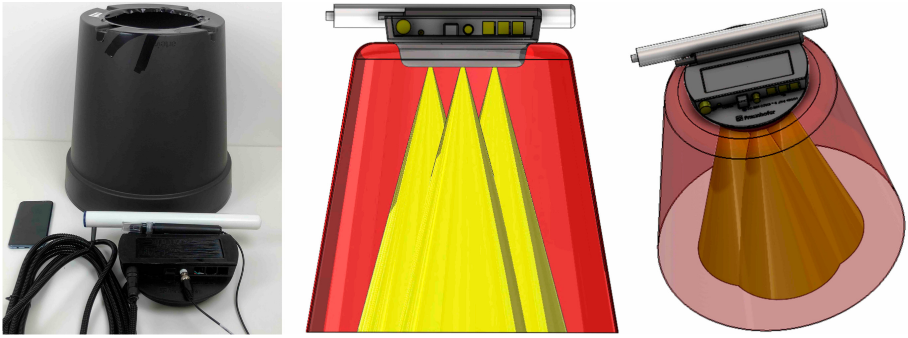


Fig. 5. Prototype and validation of the cabinet for controlled light.

light. The projected views of the expected FOV of each LED are shown in the transparent drawings.

The two elements, when assembled, transform into a single one and create a field with absence of exterior light fulfilling the computer vision requirement for non-existence of light to allow better image acquisition. The weight of the sensing box combined with the weight of the internal components make the box maintain pressure in the cabinet and the structure set is kept stable for field use. The sensing box fulfills the expectations of housing all components in a robust way and ensuring that they are protected. The interaction area (i.e., power button, plugging slots, warnings) with the user is functional as it also offers the slots for the placing the external probes (i.e., moisture and pH).

5.1 IoT Sensing Box Software

The Sensing Box Software is composed of three software modules, with two running in the Raspberry Pi (Camera Reading SW Module and Arduino Readings SW Module) and one running in the Arduino (Multi Sensor SW Module). These SW modules communicate between each other via three sockets, with two for the communications between the Raspberry and the user equipment connected to it through the provided Wi-Fi access point (configuration sockets and ZeroMQ sensor data), and one for the communication between the Raspberry Pi and the Arduino by serial socket.

The sensing box software architecture, as shown in Fig. 6 contains two types of sockets, a TCP-based one and a serial one. Each socket implements its own protocol based on the particularities of their type, as detailed next.

The **ZeroMQ sockets** are used for the communication between the Raspberry Pi and the UE connected to the sensing box. These sockets are implemented based on a publish/subscribe paradigm. These roles are changed for the Sensor Data Socket, here the software modules in the Raspberry Pi open the socket in publisher mode and publish the sensor data message, while the software running on the UE opens the socket in subscriber mode and consumes the sensed data.

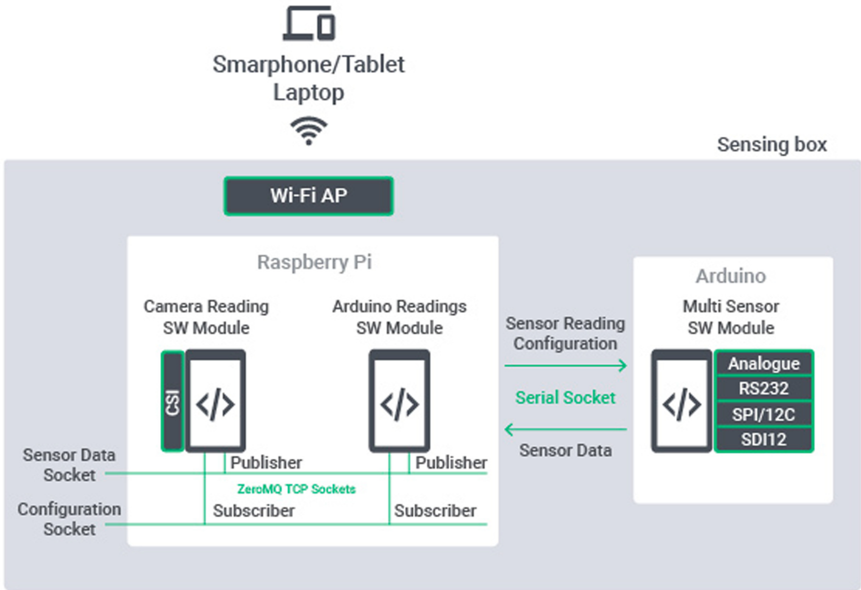


Fig. 6. Sensing box software architecture.

```
{
"configurations": [
 {"device_id": "1",
  "device_config": [
   {"config_id": "1", "config_value": "XYZ"},
   {"config_id": "2", "config_value": "XYZ"},
   ...
   {"config_id": "n", "config_value": "XYZ"}
  ]
 },
 ...
 {"device_id": "n",
  "device_config": [
   {"config_id": "1", "config_value": "XYZ"},
   {"config_id": "2", "config_value": "XYZ"},
   ...
   {"config_id": "n", "config_value": "XYZ"}
  ]
 }
]
}
                                        (a)
```

```
{
"data": [
 {"device_id": "1",
  "device_data": [
   {"sensor_id": "1", "sensor_value": ["ABC",  "GHI", "XYZ"]},
   {"sensor_id": "2", "sensor_value": ["XYZ"]},
   ...
   {"sensor_id": "n", "sensor_value": ["ABC", "XYZ"]}
  ] },
 ...
 {"device_id": "n",
  "device_data": [
   {"sensor_id": "1", "sensor_value": ["XYZ"]},
   {"sensor_id": "2", "sensor_value": ["XYZ", "GHI"]},
   ...
   {"sensor_id": "n", "sensor_value": ["XYZ"]}
  ]
 }
],
"timestamp": "XYZ",
"message_id": "XYZ",
"sensingbox_id": "XYZ"
}
                                                          (b)
```

Fig. 7. (a) Configuration and (b) Sensor data messages.

The information exchanged in these sockets follows a well-defined structure based on JSON (JavaScript Object Notation) data-interchange format. Figure 7 outlines this structure. The configuration message (Fig. 7a) is composed of an array of devices, identified by their unique id (device_id), which also have a set of configurations (device_config) properly identified by an ID that is unique to that device context (config_id) and composed of the respective configuration value (config_value). A device on this context represents a sensor with one or multiple sensing capabilities (for example the Sentek drill & drop soil sensor is capable of sensing moisture, salinity and temperature, so it is a device with multiple sensors, or sensing capabilities).

Following this structure, new devices and device configurations can be added to the configuration message simply by adding new elements to the array. The socket and the Arduino Readings SW Module are agnostic in what regards the information present inside this structure, so to add new devices and device configurations to the configuration message, the developer only needs to update the software running on the UE and the Multi Sensor Software Module running on the Arduino to correctly create and interpret the new devices and configurations.

The sensor data message (Fig. 7b) is composed of an array of devices, identified by their unique id (device_id), having a set of data values (device_data), also identified by an ID that is unique to that sensor context (sensor_id) and respective data value (sensor_value). As in the configuration message, a device on this context represents a sensor with one or multiple sensing capabilities, and each sensor inside the data array represents the various sensors in the device (considering again the Sentek drill & drop soil sensor, it is a device with multiple sensors - the moisture, salinity and temperature).

Based on this structure, new devices and/or sensors and their sensed data can be added to the sensor data message simply by adding new elements to the arrays. The socket and the Arduino Readings SW Module are again agnostic in what regards the information present in this structure, so to add new devices and/or sensors and their sensed data to the sensor data message changes are only required in the software running on the UE and the Multi Sensor Software Module running on the Arduino to suitably create and interpret the new sensor data. The **Serial Socket** is just a relay for the data available on the ZeroMQ socket that allows configuration and sensor data to reach and leave the Arduino, respectively.

The presented software architecture is easily integrated in the sensing box hardware and, straightforwardly, communicates with its default sensors, while providing a communication interface for the UE. In addition to this, the software architecture allows for an easy integration of new sensors just by including the sensor driver on the Arduino Multi Sensor SW Module, and its configuration and sensing data in the configuration and sensor data messages. With this, the addition of new sensors in the sensing box is limited to modifications on Arduino software, which is by design thought for low to medium level technical users.

6 Conclusions

This paper presents the recent developments of an IoT sensing box for collecting data on the soil and surrounding environment. The box is coupled with soil image analysis through computer vision to improve the reliability of the sensed data, and to ultimately help small-scale farmers by improving their yields and income. The selection of the hardware to build the sensing box was performed having in mind a DIY approach, and aligned with the box's requirements of familiarity, low-cost, simplicity and market availability on the target deployment countries. The software was developed to allow an extension by low to medium level technical users, and can be easily adapted to new application scenarios and use cases. The image acquisition module was designed and configured to answer the requirements of the computer vision for soil classification. The design details of the protective casing to house all the hardware (i.e., SBC, microcontroller, sensors, illumination, mounting parts) that compose the IoT sensing box were presented in detail.

As the proposed sensing box is currently at prototype stage, we have validated a few aspects in a controlled, in-lab environment, namely i) the software architecture and socket communication were tested with sensor data being collected and made available in the sockets; ii) the image acquisition module was finetuned to guarantee high quality images for the soil image analysis; and iii) the protective casing was validated concerning the fitting between of the sensing box into the cabinet, assembly of all components and cabling, and interaction of the user with the sensing box.

The next steps in the research path are to deploy the prototype in real rural environment and to validate the technology in such scenarios. The deployment fields are those of the Project AFRICA's partner countries, namely Ghana, Uganda, and South Africa. The field tests will be carried out with farmers and soil experts of each country, and shall help improving the prototype towards its final version.

Such field tests shall include the validation of the set of chosen hardware (i.e., boards and sensors), the ability to provide accurate readings on the target parameter (i.e., pH, moisture, air temperature, and light), the communication between the sensing box and user equipment, energy consumption tests, tests with green-energy solutions to power the sensing box, and usability tests.

Additionally, to correctly apply the computer vision study, camera parameters may have to be recalibrated during tests in the real crop fields. Factors like wind conditions and temperature, may affect camera and LED behavior, as creating motion blur or variate field-of-view in the images. In addition, more wavelengths of light should be tested besides the current white LEDs. We started with white light because our soil classifier with artificial intelligence models were trained with this type of images. However, we expect that the estimation of soil type can be obtained from the colour information presented in those alternative images to predict and complement the texture information

Finally, we expect to have image datasets collected with the prototype that will allow us to assess some challenges of applying transfer learning, from 2D profiles of soil samples cut in depth to 2D soil samples of the surface acquired by our camera system.

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