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Low-Cost Monitoring System for Hydroponic Urban Vertical Farms

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***Abstract*—**This paper presents the development of a low-cost monitoring system for a hydroponic urban vertical farm, enabling its automation and a quantitative assessment of the farm performance. Urban farming has seen increasing interest in the last decade thanks to the development of energy efficient and affordable LED lights; however, the optimal configuration of such systems (i.e. amount of nutrients, light-on time, ambient temperature etc.) is mostly based on the farmers' experience and empirical guidelines. Moreover, even if simple, the maintenance of such systems is labor intensive as it requires water to be topped-up periodically, mixing of the nutrients etc. To unlock the full potential of urban farming, a quantitative understanding of the role that each variable plays in the growth of the plants is needed, together with a higher degree of automation. The low-cost monitoring system proposed in this paper is a step toward filling this knowledge and technological gap, as it enables collection of sensor data related to water and air temperature, water level, humidity, pressure, light intensity, pH and electric conductivity without requiring any human intervention. More sensors and actuators can also easily be added thanks to the modular design of the proposed platform. Data can be accessed remotely via a simple web interface. The proposed platform can be used both for quantitatively optimizing the setup of the farms and for automating some of the most labor-intensive maintenance activities. Moreover, such monitoring system can also potentially be used for high-level decision making, once enough data are collected.

***Keywords*—**Automation, hydroponics, internet of things, monitoring system, urban farming.

I. Introduction

THE rapidly increasing human population and the systems we use to feed ourselves is putting unsustainable pressure on the Earth's ecosystems. Therefore, we urgently need alternative ways to produce food. Hydroponics, and more specifically urban Vertical Farms (VF), present a compelling solution to some of these problems [1]-[3]. Producing food in the cities where it is needed dramatically reduces packaging, transport and storage, and the food losses caused by these processes, and provides the freshest produce possible, alongside meaningful employment in the areas it is needed most [4], [5].

Most medium to large-scale Urban VFs usually have their own integrated sensing and control systems, but there are two important use cases where no viable solution currently exists. The first is for farms whose business model includes supplying mature produce to cafes and restaurants for final stage growing in systems situated on the food premises. The second is for systems installed as a feature or focus point within a workplace or community center, or as an educational tool within a school, college or university [6]. For these systems simple, scalable and affordable monitoring and control systems are required to allow them to be maintained by non-expert users, and for cases where they are maintained by an external company, for remote access and control. Data gathered from such systems also provides interesting information on how different plants and systems perform in widely different settings, and is of great interest for data mining.

Some attempts in developing low-cost monitoring system to be used in this context have been recently made. For example, in [7] the authors have proposed an Arduino-based system to monitor growth of red onions and correlate it with environmental factors such as humidity and light received, but it crucially lacks sensors related to the amount of nutrients provided for the plants. A similar system, still lacking information about nutrients, has been proposed in [8] as well. Internet-of-Things techniques, where sensors are used to collect data about the farm and the plants, and a microcontroller connected with the network send such data to a central server, have been proposed in [9], [10]. In [11], the authors addressed the problem of accurate dosing of nutrients by developing an Arduino-based automatic system that monitors the level of the nutrient solution and automatically add nutrients whenever the level is below a user-defined threshold. Similarly, a system to automatically add nutrients when the electrical conductivity of the water-nutrient solution falls below a given threshold was developed in [12].

The monitoring system described in this paper features a comprehensive set of low-cost sensors for water and air temperature, water level, humidity, pressure and light sensors, and also pH and electric conductivity sensors to evaluate available nutrients. The system is modular and built around a Raspberry Pi and implements the I^2C, 1-Wire and analogue protocols, so that additional sensors can be added easily if needed. Sensor data is sent to a remote SQL database, which is used as an access point to display current data and time series on a web page that is accessible from everywhere, so that the farm can be monitored remotely. Feedback control on the sensory information can be easily implemented if needed.

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The paper is organized as follows. The experimental setup used to collect the data is described in Section II, whereas the choice of sensors is discussed in Section III. The data collection and transmission platform proposed in this paper is described in detail in Section IV. Finally, some conclusions are reported in Section V, together with suggestions for further work.

II. Experimental Setup

The farm consists of a wheeled frame that has been designed to be compact and lightweight so that it can be moved easily. It is made up of modular aluminum bars and connectors (Aluminium Warehouse, UK) in order to simplify its mounting as well as to reduce its cost.

The frame is composed of two different parts, as shown in Fig. 1: a fixed part and a telescopic part.

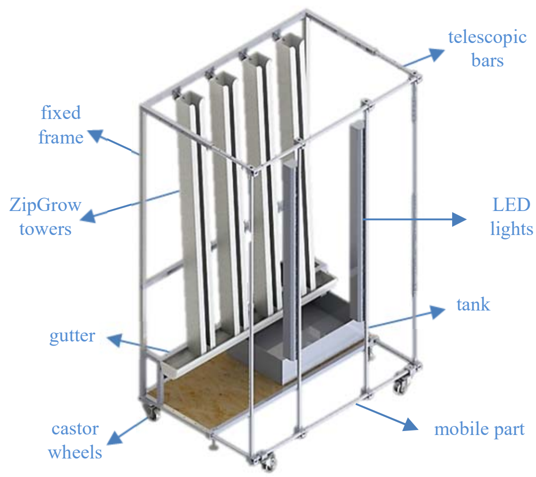

Fig. 1 Frame of the urban VF used in this project

The fixed part is composed of square aluminum bars of 25 mm^2 size connected together using three-way and T-shaped connectors. This part hosts four ZipFarm towers (ZipFarm, US) arranged vertically and hanged from the frame via four hooks. Each tower contains an inert medium that provides an anchorage to the roots of the plants and cotton stripes to keep the root zone humid. On the other hand, the telescopic part hosts two vertical LED lights (B100, Valoya, Finland) that replicate the effects of the natural outdoor sunlight. This mobile part gives the opportunity to adjust the distance between the LED lights and the plants according to the amount of lights required by the latter.

In hydroponic farms, soil is replaced with an inert medium and the nutrients are provided together with water through a piping system. In the setup proposed here, a tank stores at most 33 L of nutrients solution (3 mL of Vitalink Hydro Max Grow SW part A and part B for each liter of water) at the bottom of the farm. The nutrients are pumped to the top of each tower. The solution, after flowing through the root zone under gravity, is then collected by a gutter which finally returns it back to the tank, thus creating a closed-loop system. The tank is covered with a lid to minimize evaporation, thus reducing waste of water. An UV sterilizer is also present in the closed-loop water system for safety reasons.

III. Sensors

The sensors adopted in the system proposed in this paper have been selected according to two main criteria: collect useful information about the status of the VF and minimize cost to promote wide adoption by end-users. Such sensors can be broadly classified into two categories:

- Water tank sensors: water temperature, water level, acidity (pH), nutrients quantity (EC);
- Ambient sensors: pressure, humidity, temperature, light.

The water tank sensors check the condition of the nutrient solution inside the tank. Indeed, in hydroponic systems, the nutrient solution represents the most important element of the farm itself, providing both the water and the nutrients the plants need to grow.

The Electrical Conductivity (EC, DFRobot, Shanghai) and the acidity (pH, DFRobot, Shanghai) sensors are analogue sensors and detect the chemical conditions of the solution; more specifically, the former detects the total amount of nutrients inside the tank, whereas the latter detects the pH value of the solution. The pH value must be in a specific range - depending on the crop - as it plays a crucial role in the chemical reactions that make the nutrients available to the plants. Before installation, both sensors have been calibrated with the calibration kits provided by the manufacturer.

The temperature of the solution is important as well, and it is measured using a waterproof sensor (DS18B20, Dallas Semiconductor, US), which is based on the 1-Wire protocol to send the data to the Raspberry Pi board.

As mentioned previously, the nutrient solution system operates in a closed-loop, thus limiting the waste and the consumption of the solution itself. However, most of the nutrient solution is used by the plants to get the nutrients they need to grow, especially in the first period of their life. In order to always guarantee that a minimum amount of solution is available in the tank, the level of the solution left inside the tank is detected via an ultrasonic sensor (HC-SR04, OSEPP, Canada). The sensor is located above the tank and measures its distance from the water surface (*d*). The level of the solution left inside the tank can be hence calculated knowing the distance between the sensor and the bottom of the tank (*D*) as:

$$Water\ Level = D - d \qquad (1)$$

On the other hand, the ambient sensors are used to evaluate the physical conditions of the environment surrounding the farm and they both implement the I^2C protocol to share the data.

A weather sensor (BME280, Bosh Sensortec, Germany) is used to measure the temperature, the pressure, and the humidity of the ambient. Moreover, an ambient light sensor (VEML7700, Vishay, US) is used to measure the quantity of light coming from the LED lights. Currently, just one ambient light sensor is used in each tower, but in the future more sensors can be spread along the height of each tower so to obtain a more accurate information about both the total amount of light reaching each tower and its spatial distribution.

Table I summarizes the features of the selected sensors in terms of accuracy, communication protocols, and cost.

Together with all the sensors described in this section, a camera (Raspberry Pi Camera) has been adopted as well. The camera takes a picture of the farm every 10 minutes to monitor the status of the plants.

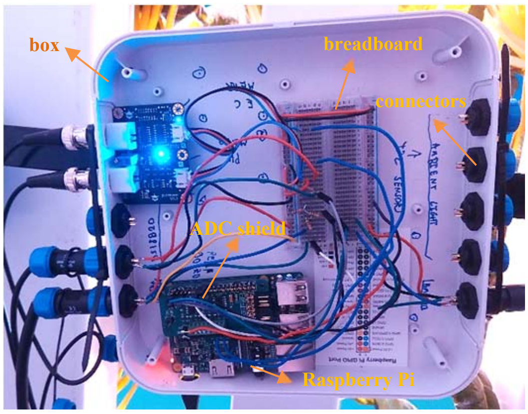

Fig. 2 Monitoring System – Hardware

TABLE I
SUMMARY OF MAIN SENSORS FEATURES

Sensor	Quantity	Accuracy	Protocol	Cost (£)
EC	electrical conductivity	+/- 5%	analogue	53.69
pH	acidity	+/- 0.1 pH	analogue	34.20
DS18B20	water temperature	+/- 0.5 °C	1-wire	5.30
HC-SR04	water level	+/- 3 mm	digital	3.70
BME280	pressure humidity temperature	+/- 1 hPa +/-3% HR +/- 0.5 °C	I^2C	11.52
VEML7700	light	0.0036 lx/ct	I^2C	7.60

IV. MONITORING SYSTEM

A. Hardware

The proposed monitoring system is built in a modular fashion around a Raspberry Pi 3 model B (Raspberry Pi Foundation, UK). All the sensors are indeed connected to this platform via a combination of I^2C, 1-Wire and analogue protocols. Moreover, since the Raspberry Pi is not capable of natively acquiring analogue signals, an Analog to Digital Converter (ADC) shield (ACDPi, ABelectronics, UK) has been adopted to convert such signals in digital ones.

All the electronic components - the Raspberry Pi platform, the ADC shield, and a breadboard for the wiring connections - are stored inside the waterproof box shown in Fig. 2. Waterproof connectors and cables have been used to connect the sensors to the box. The proposed solution is modular, composed of standard off-the-shelf components only, so easily replicable to other farms. Additional sensors can be added easily whenever needed as well.

B. Software

The developed software allows storing the sensors data in a remote database and showing them on a web page (Fig. 3). The software is composed of three main parts:

a) Sensors: scripts to collect data from the sensors. A separate function for each sensor, returning the sensor reading every time is called, has been developed and then integrated in a main routine to improve modularity.
b) Database: code to deal with the communication between the sensors and a database storing all the data. More specifically, the script calls the functions from the sensors scripts and stores the value of each sensor in the database together with the timestamp of the readings. In this way, the whole time series of sensor readings is stored in the database.
c) Web: scripts used to create a web page to display the sensor values. The web page has access to the remote database, so it is possible to retrieve the stored data and show them in a user-friendly interface that can be accessed remotely.

The software uses only components that are freely available, and it requires only the sensors libraries and an internet connection for its development. The sensors scripts have been developed in Python to be fully compatible with the Raspberry Pi platform and they require only the sensor libraries to implement the reading functions.

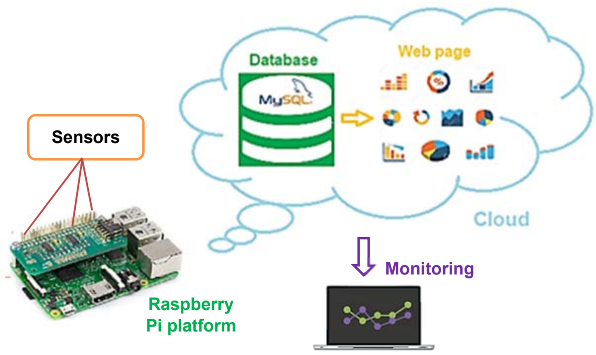

Fig. 3 Monitoring system - Software

The communication between the sensors and the database uses the free *mysql* packages that can be easily installed on the Raspberry Pi platform using an internet connection. The aforementioned packages contain the functions needed to set up the communication protocol, enabling the system to store the sensors data in the database. The database used within this project is a free MySQL database that can be accessible remotely (remotemysql.com). The structure of the database can be modified and managed using the phpMyAdmin administration tool for MySQL database.

The web page is a PHP file that shows the sensor data in a meaningful way using JavaScript dynamic charts. Currently, the web page shows the last reading of each sensor together with the trend of the water temperature of the last 24 hours, as shown in Fig. 4. The page is updated every hour and it can be refreshed manually using the provided "Refresh" button. The web page host used within this preliminary data collection is 000webhost (000webhost.com). The page displaying the sensor readings is always online and is accessible from everywhere, thus allowing a remote monitoring of the hydroponic farm.

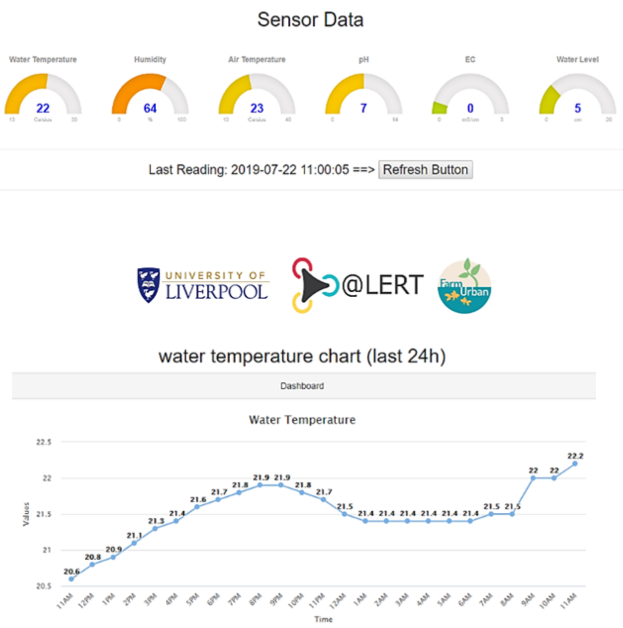

Fig. 4 Web page (hydroponicsvertical.000webhostapp.com)

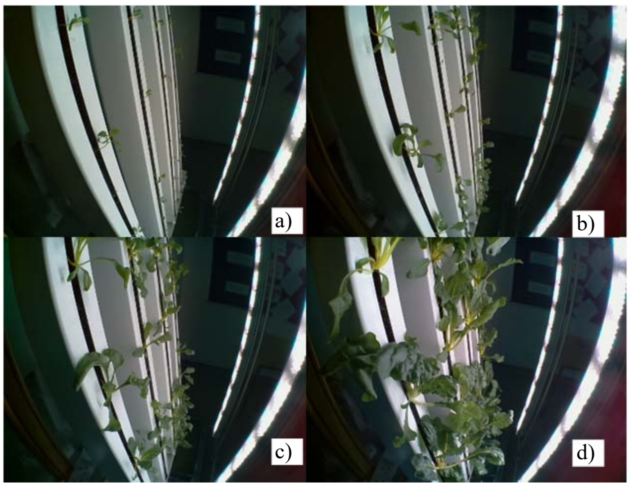

Fig. 5 Crops growth: a) initial phase; b) after 15 days; c) after 30 days; d) after 45 days;

The systems were tested by planting the farm with chard. Both the towers and chard were provided by Farm Urban. The growing process has been thoroughly recorded using the Raspberry Pi Camera (Fig. 5). The full time series of pictures captured by the camera are stored in a local database. The pictures can be used to evaluate the status of the crops, such as color and height, and set the farm parameters (water flow rate, amount of nutrients, light intensity, etc.) accordingly.

In our farm, a plastic box of 33L has been adopted as water tank and liquid nutrients have been added to create the solution (3mL every liter of water). A rectangular slot has been manufactured on the lid of the box to insert a 3D printed rectangular support hosting the water tank sensors altogether, as shown in Fig. 6. Currently, the tank is refilled manually, but this process can be easily automated using a water reservoir and a valve. Indeed, the valve can let the water flow from the reservoir to the tank according to the value coming from the HC-SR04 ultrasonic sensor.

During the whole experiment, the LED lights have been switched on for 16 hours per day and off for the remaining 8 hours. Table II shows an extract of timeseries regarding water temperature, humidity, pH, EC and air temperature, as stored in the remote database.

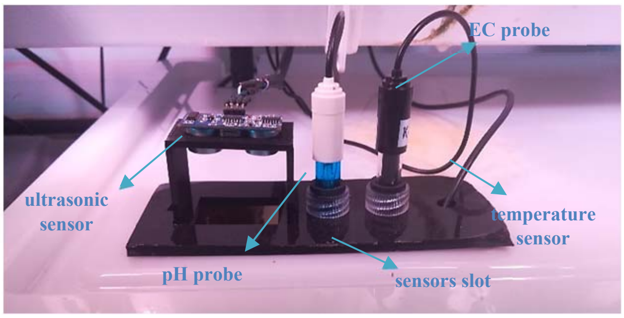

Fig. 6 Water tank sensors hosting kit

TABLE II
EXAMPLE OF SENSORS READINGS

Reading Number	Water Temperature (°C)	Humidity (HR %)	pH	EC (ms/cm)	Air Temperature (°C)
1	18.6	55.4	7.5	0.38	19.4
2	18.9	51.9	7.7	0.37	19.8
3	19.4	49.7	7.6	0.38	20.1
4	20.1	50.6	7.7	0.39	20.8
5	20.6	48.7	7.8	0.41	21.4
6	20.8	57.4	7.6	0.43	22
7	20.4	63.9	7.4	0.43	21.3
8	19.9	62.6	7.2	0.41	19.9
9	19.2	58.6	7.3	0.38	19.6
10	18.4	58.2	7.6	0.36	18.7

V. Conclusion

This paper presents the development of a low-cost monitoring system for hydroponic VF that can be used to monitor the system remotely and help to quantitatively understand the role played by every parameter in the crops' growth. The proposed platform is composed of readily-available inexpensive sensors and modular components, therefore it is affordable as well as simple to set up and use. The system can hence be easily replicated and other sensors can be added if needed.

The data acquired by the sensors are shown in a web page in a user-friendly way. The web page is accessible remotely, so it is possible to know the farm conditions from everywhere.

The system can be used to collect the sensor data to carry out a quantitative assessment of the farm and can also be used for high-level decision making, once enough data are collected. Moreover, the proposed monitoring platform represents a starting point to make the farm truly autonomous, using the sensor data as input signals for the activation of fans, valves, lights, motors and so on. Such a system can unlock the potential of hydroponics, making it a valid alternative to ordinary agriculture for facing future climate changing related challenges.

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