UrbanBox: a Low Cost End-to-End Platform for Smart City Sensing

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***Abstract*—This paper presents a low cost end-to-end and open-source urban sensor node, called UrbanBox, which is based on the concept of the Internet of Things (IoT). Through the sensing platform made by multiple UrbanBox nodes, users can collect, visualize, and store the real-time data from urban environments. The platform can serve as a tool for developing data-rich smart cities. This paper presents the design, data collection architecture, and the sensors validation process for the implemented prototype.**

***Index Terms*—Internet of things, smart city, sensor network, environment monitoring, open-source hardware.**

I. Introduction

It is estimated that the urban population will account for 72% of the overall world population by 2050 [1]. Traffic jams, noise level, and air pollution are considered to be major problems facing modern cities today. The development of intelligent monitoring systems based on the Internet of Things (IoT) approach will assist both citizens and governments to deal with such issues and improve the quality of life. IoT is a network of physical devices which consists of software and sensor that have the ability to communicate with each other.

There are various commercial monitoring systems in the market; however, most of them are *expensive*, *proprietary*, and *difficult to implement*. Moreover, most of these platforms require knowledge and expertise to be assembled and installed. Despite the fact that these systems are effective, they are designed to connect to proprietary platforms. The users do not have full control and cannot modify any parts of the hardware system. As a result, such designs are non-modular. The commercial solutions limit the experience and do not provide flexibility to the end user.

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In order to develop an urban-based IoT platform which will address the existing challenges faced by commercial designs, the monetary costs must be examined. In addition, real-time data collection is an important feature that must be part of the design. A powerful microprocessor, sufficient memory storage, an efficient power supply, and accurate sensors are several physical parts that must be included. The cybersecurity is also another aspect that must be explored [2], [3]. It is important to provide network security between wireless nodes. In this regard, protocol validation and network diagnosis are also significant challenges for the software development of IoT [4], [5].

In this paper, the main objective is to develop a real-time urban-based environment and transportation monitoring platform. Inexpensive and high precision components will be used in the design. The collected data are transmitted and stored at cloud-based database and displayed on the Application Programming Interface (API) for visualization.

The rest of the paper is structured as follows: Section II presents the related work in sensor kit solutions, different research and development efforts as well as government related smart city projects. Section III discusses the design of the UrbanBox platform and its main components, while Section IV presents the data collection process and visualization. Section V describes the validation procedure of the UrbanBox sensors, and Section VI provides conclusions and future work for the project.

II. Existing Projects

There are numerous of educational sensor development kits available in the market. Such solutions allow the utilization of multiple sensors on one device without high installation costs. For example, the Elegoo 37-in-1 box sensor kit is a development kit for beginners to develop and collect data [6]. Most of its sensors, however, are not accurate enough for research or wide-area deployment. Another example is a weather station kit from Sparkfun [7]. Although it offers several different sensors as a shield, it does not have a flexible configuration.

Different researchers have developed energy-efficient wireless sensor networks based on IoT technology for smart city monitoring. They monitor various fields such as environmental changes and natural disaster prevention [8], [9]. Mois *et al.* proposed three different wireless sensor nodes based on IoT and different communication methods [8]: Datagram Protocol based on Wi-Fi communication, Wi-Fi and Hypertext Transfer Protocol, and Bluetooth Smart. Nguyen *et al.* proposed a wireless networking sensor node for environment monitoring based on IoT and cloud computing [10]. Every node consists of different components including a low-power system-on-a-chip integrated with Bluetooth, and a multi-functional sensor array to detect different environmental parameters.

Existing government projects for smart city platforms include the SmartSantander [11], IBM's Green Horizons [12], and InterCityAir [13]. The SmartSantander project, located in Santander, Spain, is a city-scale experimental research facility for smart cities services and application. It provides an advanced experimental environment for IoT technology researchers and developers. The project has more than $12k$ IoT devices deployed around the city collecting various environmental data. IBM's Green Horizons project is a government effort in Beijing, China which uses the latest technologies of IoT and artificial intelligence to monitor air quality. IBM's solution requires a high deployment cost to be implemented. InterCityAir is a city-wide air quality project taking advantage of IoT and low power consumption sensors in the UK. Although data is transferred in real-time, the cost of the project makes it impractical for smaller cities.

The Chicago Array of Things (AoT) project is another networked urban sensor project based on IoT. The nodes provide location-based real-time data on environmental measurements, infrastructure, and city activity [14]. AoT is a collaborative effort and supported by the National Science Foundation, the University of Chicago, Argonne National Laboratory, the City of Chicago and other industry. In the project, over 500 sensor nodes around the city of Chicago are installed which collect different measurements. These measurements include air quality, climate, and noise. AoT data is published openly and freely [14].

TABLE I
URBANBOX COMPONENTS

A/A	Component Model	
1	Micro-controller(Arduino Uno) [16]	
2	Mini Cellular GSM(FONA 808) [17]	
3	TTL Serial JPEG Camera(PTC08) [18]	
4	Temperature and Humidity Sensor(DHT22) [19]	
5	Light Dependent Resistor (GL5528) [6]	
6	Multi-channel (MICS-6814) gas sensor [20]	Carbon monoxide
		Methane

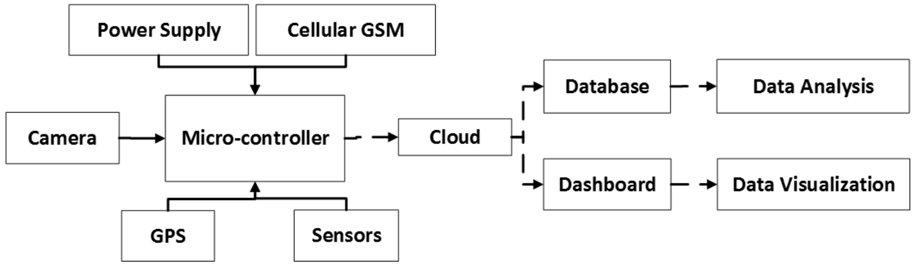
Padova Smart City (PSC) is another smart city project the utilizes IoT technology [15]. The project supports monitoring of different environmental parameters such as atmospheric gases, temperature, noise, and other parameters. The IoT sensor nodes, installed on street lighting poles, transmit data through the city wireless network. Each node is powered by an external battery [15]. The collected data is used by city administration to improve life quality of Padova city citizens.

III. DESIGN

Most cities experience air pollution, traffic congestion, and light pollution on a daily basis. Due to these issues, UrbanBox has been designed to capture temperature, humidity, light intensity levels, toxic gas concentration, air particles, and vehicle count. The integrated camera on the UrbanBox allows for users to monitor traffic flow. Through this set of measurements, urban problems that plague our lives can be identified and addressed.

In order to transit and collect the measurements from UrbanBox, the project utilize 4G cellular networks. The 4G communication provides high speed and flexibility. The Message Queuing Telemetry Transport (MQTT) has been selected as the messaging protocol. MQTT makes it possible to access data in real-time. This provides a fast transaction rate which eliminates bottlenecks allowing data to flow from sensors to the server.

The Arduino Uno has been selected as the hardware micro-controller (MCU) platform for UrbanBox. Its purpose is to integrate and coordinate all sensors. The selection of Arduino Uno is based on the fact that is a widely used and well-documented low-cost platform. The sensors used in the first version of UrbanBox are shown in Table I. They have been selected after various experiments based on their accuracy, time response, and power consumption. All sensor nodes are connected with



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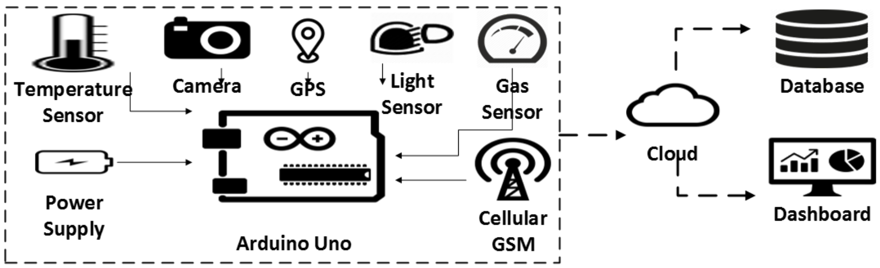

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Fig. 1. The overall architecture of UrbanBox: (a) flow diagram, and (b) components of UrbanBox.

the Arduino platform and have a total input current requirement of $\approx 337.5\ mA$ and a supply voltage of $5\ V$.

The DHT22 sensor is used to capture temperature and humidity data. The MICS-6814 measures eight different types of gas which include carbon monoxide, nitrogen dioxide, methane, ethanol, ammonia, hydrogen, propane, and iso-butane. Carbon monoxide and methane are collected in UrbanBox since they are most typical for gas leakage [21]. GL5528 is a light sensor to measure ambient brightness. By converting the analog voltage (0-5V) to a digital value, the amount of light and darkness around the sensor can be determined. The camera module PTC08 is attached to the UrbanBox for monitoring the traffic flow. The FONA 808 shield is used to provide 4G connectivity. It is also equipped with a Global Positioning System (GPS) breakout which captures the location and the time for measurement synchronization.

The architecture of the UrbanBox is illustrated in Fig. 1(a). The solid lines indicate wired connections. The dashed lines indicate wireless connections through communication links. The collected data from the Arduino MCU and the sensors are transmitted and stored in a remote cloud-based database. This gives users the ability to access current or historical data at any moment. For data visualization, an online dashboard API provides the ability to monitor real-time changes. Fig. 1(b), shows all the modules in the UrbanBox end-to-end design including the hardware and sensors as well as the connection to the remote database and the dashboard API. Fig. 2 presents how each one of the UrbanBox sensor components of Table I (FONA 808, PTC08, DHT22, GL5528, Mics-6814) are connected with the Arduino MCU. Fig. 3 is shows the first prototype of UrbanBox installation.

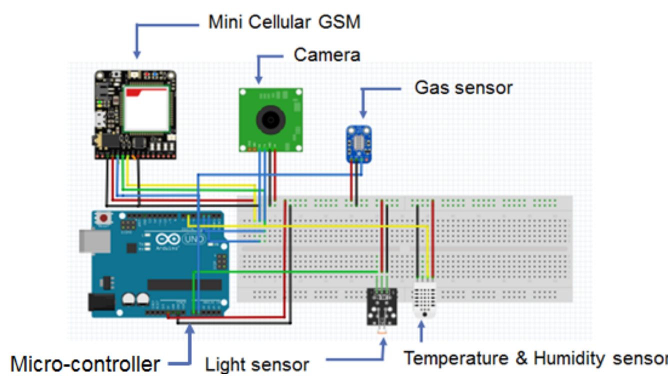


Fig. 2. Hardware layout of UrbanBox.

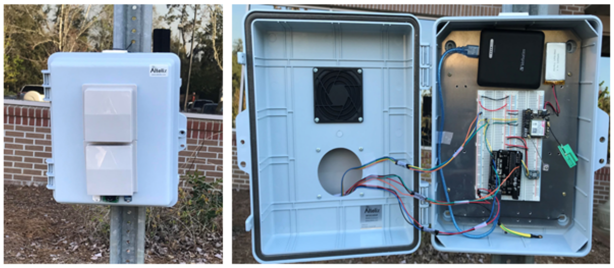


Fig. 3. UrbanBox prototype.

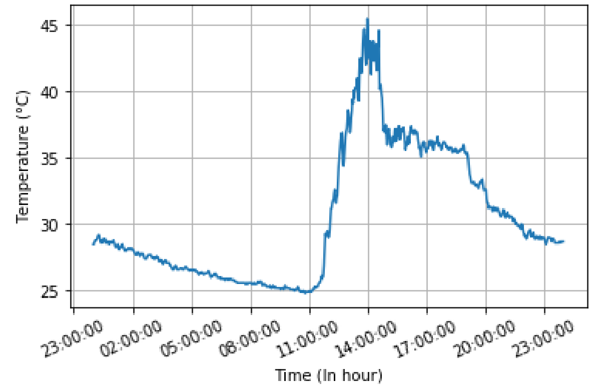
Fig. 4. API dashboard for real-time visualization.

IV. Data Collection & Visualization

The data collected from each UrbanBox is recorded and visualized for further analysis. This data includes temperature, gas concentration, humidity, light intensity, longitude, latitude and time. The camera captures the traffic flow. It records the image data onto an SD card separately due to the size of the images. The data transmission rate depends on which sensor is being utilized.

As mentioned in Section III, MQTT facilitates the data transmission. After every transmission session has been completed, the user will have access to the real-time dashboard and thus to all of the collected data. The dashboard API is presented in Fig. 4. The dashboard updates in every second with multiple readings including humidity in percentage, the temperature in degree Celsius, and light intensity . Gas sensor indicator shows the amount of air pollution (NO_2 and CO) from 1 to 20 ratio, where 20 is the highest amount of the air pollutants. The UrbanBox provides location coordinates which display on the left side of the dashboard.

In regards to data visualization, Fig. 5(a) shows how the temperature changes in Tallahassee, Florida over a typical day during June 2018. Similarly, the data for humidity and light intensity are shown in Fig. 5(b) and Fig. 5(c), respectively. Fig. 6 shows the result of a vehicle detection process. The raw picture captured from the UrbanBox camera and stored in the SD card is transferred to an image processing routine (Cascade Classifier in OpenCV) for vehicle detection [23].



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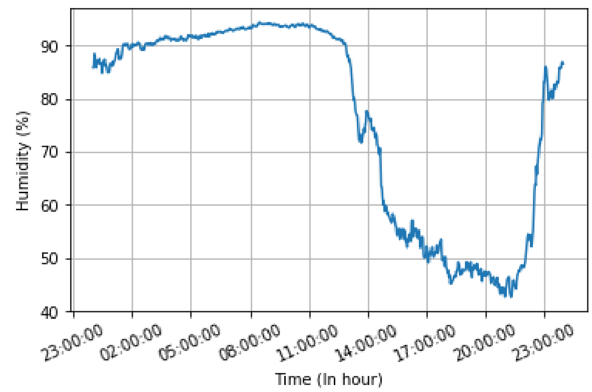

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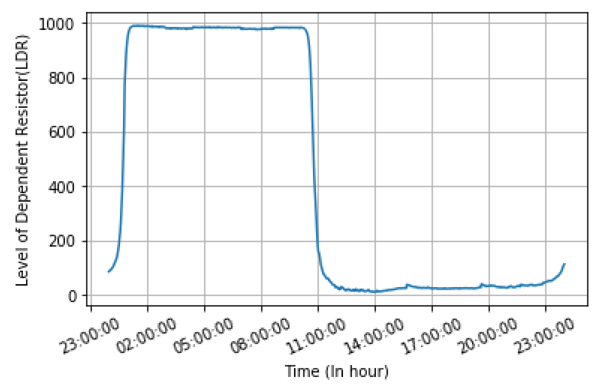

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Fig. 5. A sample data for one day.: (a) Temperature, (b) Humidity, and (c) Light intensity data [22].

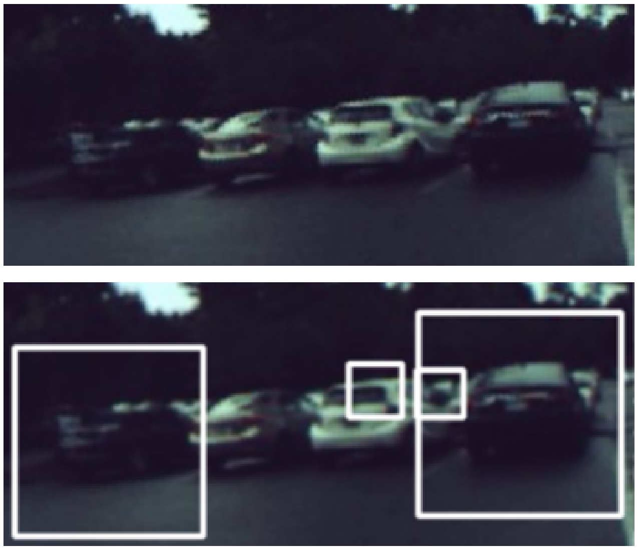


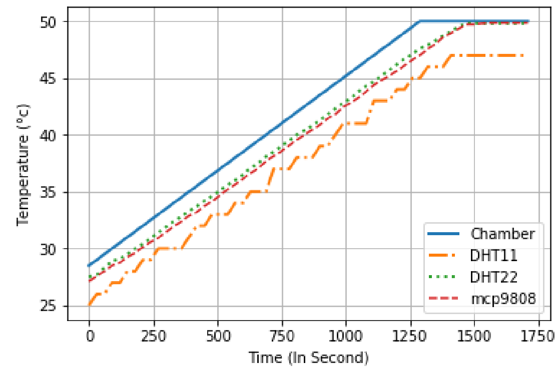
Fig. 6. Sample analyzed picture from the camera (vehicle detection).

V. Sensor Validation

Although sensors are tested and validated by the manufacturer, additional tests are required to confirm their performance and data quality. The differences between manufactured sensors can be critically important in monitoring extreme weather conditions. Three components were selected to be tested and validated: the temperature sensors, the multi-channel gas sensors and the GPS receiver [24]–[26].

In order to validate the accuracy of temperature measurements, three different temperature sensors: *i)* DHT11, *ii)* DHT22, and *iii)* MCP9808 were tested in a controlled environment chamber. First, sensors were held at room temperature. Then, we increased the chamber temperature by 1.00 °C every minute from 30.00 °C to 50.00 °C. To examine the sensors performance under extreme conditions, we kept the chamber temperature at 50.00 °C for several minutes. Fig. 7(a) shows the result. The DHT22 was the closest to the reference chamber temperature, and thus selected for the UrbanBox design.

The validation of the selected multi-channel gas sensor was done by using calibrated gas pumps with carbon monoxide and methane. The mixed gases were sprayed for 10 seconds into two sensors to measure their reaction. Fig. 7(b) shows the comparison results of two multi-channel gas sensors. When the measured output returned to the start point, a second spray was repeated for 10 seconds. The concentration of the second spray action is lower than the first one in order to test if the sensors are effective with a small amount of harmful gas. As



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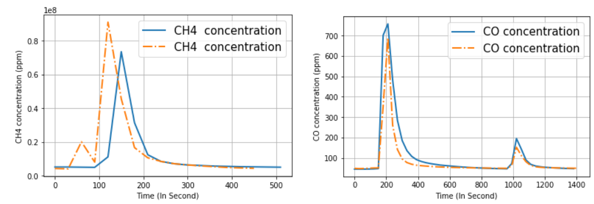

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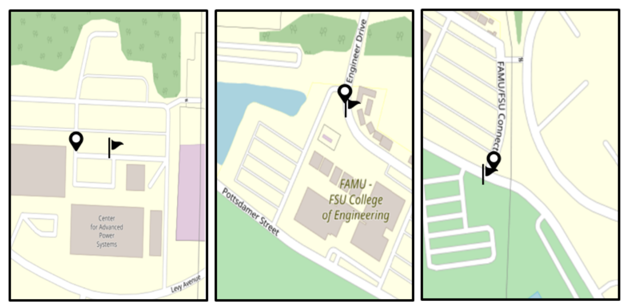

(c)

Fig. 7. Validation results: (a) temperature sensors, (b) gas sensor, and (c) GPS Comparison results.

presented, the two sensors have approximately the same trend, value, and ability to react quickly to the detectable gases.

The GPS receiver was validated by comparing the location information with a commercial GPS navigator in a car. As the results show in Fig. 7(c), the location icon shows the information from the map and the flag icon displays the data from the GPS. The location of the car was changed multiple times to collect a variety of location data. The average error between the results from GPS and the map is less than 10 meters.

VI. Conclusions and Future Work

In this paper, we presented the first version of UrbanBox sensor node which has been developed to enhance the monitoring of urban environments. Since UrbanBox was the first version, we faced some obstacles from the technical parts which affected the accuracy and quality of the data. For example, the gas sensor was tested only in an open environment, and it requires further testing in a precision gas chamber for proper validation. In addition, the current design does not take into consideration the security issues of the utilized commercial-off-the-shelf IoT technology.

We plan to improve the UrbanBox's hardware and software design. A solar panel will be added to supply power to the system. Furthermore, a weather-resistant case will be designed to protect the UrbanBox from harsh weather conditions. The quality and accuracy of sensors need to be improved as well. The reliability of data transmission and the security evaluation of the platform are additional directions the project can address in the future. Finally, more UrbanBox prototypes need to be developed to create a mesh network and facilitate system monitoring via data exchange.

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