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Urban crowdsensing by personal mobility vehicles to manage air pollution

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Abstract

The digitalization of cities and the development of smart, green, and integrated transport are societal challenges to transform cities into places with good quality of life now and in the future. The Internet of Things (IoT) comes with new advances to connect a multitude of sensing devices and even actuators, and they are presenting the cornerstone of Smart City deployments worldwide. So far, these advances have focused on static sensors in scenarios such as gardens, smart lighting, climate monitoring, or traffic management. However, moving sensors could rise the monitoring capabilities of smart cities to the next level, helping to better reflect the status of large areas without replicating fixed stations. This work proposes taking advantage of urban vehicles and, especially, personal mobility vehicles (PMVs), to implement such a perspective. Hence, a low-cost and energy-aware on-board unit (OBU) is designed to gather environmental data and support sustainable mobility applications. This on-board platform is provided with Low-Power Wide Area Network (LPWAN) communication technologies, enabling an Internet connection following an IoT scheme. The unit is equipped with sensors to measure air pollution in terms of NO_2, CO, SO_2, O_3 and PMx, noise, and weather parameters. While moving across the city, PMVs mounting this device can collect data in a crowdsensing scheme. This data feed is complemented by a set of wireless traffic sensors, and they are subject to intelligent processing to monitor pollution and mobility parameters. For this, a back-end software module is powered with temporal series analysis to generate predictions based on tendencies detected in both pollution and mobility values. A front-end Web application has been implemented to show all past, current, and predicted data, offering functionalities to monitor urban mobility, minimize travel times, detect pollution areas, and recommend healthy routes across streets with low contamination levels.

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1. Introduction

Urban pollution has become of paramount importance due to the proliferation of combustion vehicles and raising global warming conditions, which must be kept in mind to maintain healthy conditions for citizens. Although pollution and weather stations are more and more common in city landscapes, innovative solutions that help monitor air quality ubiquitously are necessary. Currently, fixed stations only reflect the current pollution in a particular area, which could not be representative of a whole neighborhood. Hence, global monitoring for a per-city study usually requires a set of fixed stations, increasing overall cost when a fine-grain analysis of pollution trend is required.

A potential solution to this problem is the provision of a set of moving sensors that, implementing a crowdsensing scheme, can survey environmental parameters across the city, taking advantage of regular routes. These sensors, connected with a proper wireless communication link could report data to a remote infrastructure for further processing.

Current mobile sensing devices and services are based on smartphone usage. However, the hardware required for environmental monitoring cannot be embedded in smartphones. The use of an Internet of Things (IoT) device offers flexibility in gathering different parameters related to pollution and weather, leaving it open to extensions. An IoT unit could be mounted on a moving platform for crowdsensing and here is where micro-mobility vehicles can come into play.

Cooperative-Intelligent Transportation Systems (C-ITS) have brought a technological revolution, especially for ground vehicles, in terms of road safety, traffic efficiency, as well as in the experience of drivers and passengers. So far, these advances have focused on traditional transportation means, leaving aside the new generation of personal vehicles that are flooding our streets. Together with bicycles and motorcycles, personal mobility vehicles (PMVs) such as segways or electric scooters are firm sustainable alternatives representing the future of achieving eco-friendly personal mobility in urban settings. These vehicles, which are gaining momentum, are perfect subjects to integrate C-ITS advances that, first, connect them to the Internet, and second, enable the development of moving sensing units for environmental monitoring.

Although there are particular proposals for using specific vehicles to measure pollution, such as recent works with drones (Vijayakumar et al., 2020), crowdsensing using personal or vehicle devices can offer more flexible solutions. Vehicular on-board units and, particularly, those aboard personal or vehicle devices can offer a flexible solution for environmental monitoring. Wang and Chen (2017) propose a model to estimate the air pollution due to road traffic in terms of CO_2, CO, NO, NO_2, $PM_{2.5/10,}$ and hydrocarbon, however, only simulation is considered. This approach is followed by Samad et al. (2022), with an embedded platform mounted on drones for air pollution monitoring. It uses the same particle matter (PM) sensors chosen for the current work; however, atmospheric measurements are not supported, and the unit does not report data using wireless communications. Kaivonen and Ngai (2020) describe a solution to monitor air quality in buses using commercial equipment. Lin et al. (2022) describe a solution to monitor air quality in cities using a common vehicle but using commercial equipment adapted for air intake and data collection for post-processing. In Solomon et al. (2020), the results obtained from a mobile solution using Google cars are validated against certified fixed stations. As can be seen, there are previous works betting on off-the-self devices mounted on vehicles, but there are few works developing special hardware. For instance, in Wang et al. (2021), both a prototype and an intelligent analysis of the data gathered are carried out, demonstrating the potential of mobile sensors. However, as far as we know, there are no particular solutions exploiting urban crowdsensing with micro-mobility out of our own research line (Rubio-Aparicio and Santa, 2023).

In this paper, we present a whole crowdsensing platform for environmental and mobility monitoring in cities. PMVs are equipped with a prototype of an On-Board Unit (OBU) to gather NO2, CO, NO and PMx, noise, and weather parameters. The proposed on-board platform is developed based on Low-Power Wide Area Network (LPWAN) communication technologies, enabling an Internet connection following an IoT scheme. A set of sensors are proposed to measure traffic density, also connected using LPWAN. Then, data collected from vehicles and road sensors are subject to intelligent processing to monitor pollution parameters and provide services to optimize urban mobility, minimize travel times, detect pollution areas, and recommend healthy tracks across streets with low contamination levels. An experimental pilot using e-scooters is deploying in the city center of Cartagena (Spain). The remainder of the paper describes the overall architecture in Section 2, base hardware and software development in Section 3, data processing and visualization tools in Section 4 and finally, concluding remarks in Section 5.

2. System architecture

Environmental monitoring using a crowdsensing approach with multiple devices moving in no pre-set patterns around the city allows for improving global and localized environmental awareness. The general architecture of the proposed solution is shown in Fig. 1. On-board units are attached to personal mobility vehicles, such as e-scooters, for street-level data collection. These, while moving around the city, perform continuous monitoring of parameters related to air quality, noise pollution, and weather variables. At the same level, sensors installed at key streets collect data about traffic density. Both embedded OBUs and traffic sensors are connected to a wired network infrastructure using LPWAN communications. Given that communications imply a substantial part of battery consumption, using IoT communication technologies reduce the energy impact of networking operations.

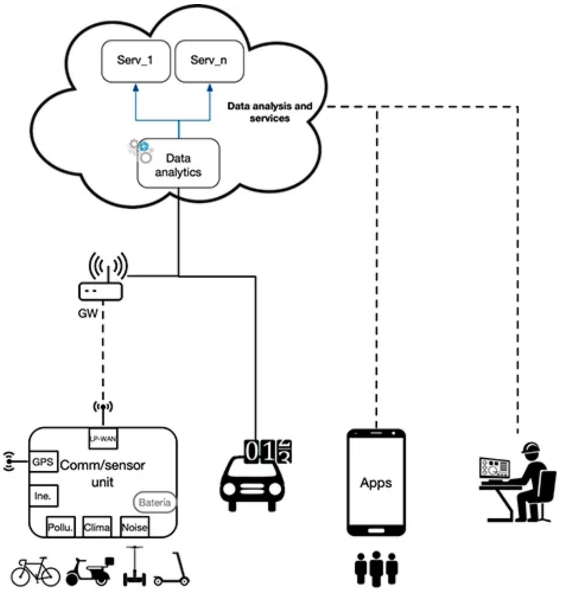


Fig 1. Architecture of the proposed solution

Data collected from sensors are pre-processed for the case of on-board units and then both OBU and infrastructure sensor data are sent to a cloud infrastructure, through an LPWAN gateway wired with a data processing infrastructure. Here short/medium-term predictions regarding pollution and mobility parameters are carried out per geographical. Intelligent algorithms using machine learning and time series are used for pollution indexes interpolation and prediction in geographical grids. A Web-based application has been developed to easily monitor environmental conditions, receive alerts, visualize urban pollution per zones, and create healthy routes in a city. This tool offers differentiated access to regular users (e.g., citizens) and professional operators (e.g., city administration).

3. Development of the monitoring solution

3.1. OBU description

The OBU design envisioned to provide connectivity and crowdsensing capabilities to PMVs is shown in Fig. 2 and described in detail in Rubio-Aparicio and Santa (2022). It is an embedded design provided with computing, sensing, and communications capabilities to cover the needs of the special scenario under consideration.

A System-on-Chip (SoC) has been selected to carry out the overall control of the OBU operation and manage communications. This helps to reduce the number of hardware components and, therefore, the size, power consumption, and complexity of the unit. It integrates a CPU with embedded flash memory, diverse digital and analog peripherals, as well as a low-power sub-gigahertz RF transceiver. The usage of an internal antenna is preferred to achieve a more compact unit as long as the wireless link quality is adequate. To measure air quality, the most relevant contaminating gases for human health are considered, such as CO, NO2, SO2, and O3. For the case of temperature and relative humidity, a combined sensor is used to reduce the number of components. Since air quality sensors are located inside the case and the vehicle can move at a limited speed, a forced air intake is implemented using a low-power and silent fan. Noise pollution is measured by an electret microphone, whose output signal is amplified, discretized by the analog-digital converter (ADC), and processed in the SoC, to finally obtain the current noise peak value. A Global Navigation Satellite System (GNSS) receiver is included to get geographical coordinates. The GNSS antenna should be placed with a clear path to the sky to improve signal acquisition. A Lithium battery is considered as the electric power source, meeting requirements of reduced weight, high energy density, and thin form factor. Additionally, we have added a basic user interface to show the operational status of the unit, such as the battery level, network link status, as well as the latest acquired pollutant values.

Fig 2. On-Board Unit (OBU) installed on an e-scooter. Source: Rubio-Aparicio and Santa (2022)

The embedded software of the OBU has been coded in MicroPython, following a scalable approach that allows future adaptation to other sensors, communication transceivers, or application needs. It uses threads for simultaneous management of SoC peripherals, and a fault-tolerant implementation has been carried out for continuous operation upon sensor failure. The user interface has been implemented using the OLED screen and a single button, offering general status information, sensor reads, GNSS coordinates, and operation counters.

The packet structure has been defined to optimize the available LoRa bandwidth, hence, reducing transmission errors and time on air. The packet contains metadata about the quality of measurements, including position accuracy and the stabilization status of all sensors. All transmissions require acknowledgment, with a maximum of 5 retransmissions before dropping. This improves network reliability under mobility and signal blockage in urban settings.

Current settings involve a minimum movement of 100 meters to report sensor readings. This provides enough resolution when gathering pollution data, considering that multiple units could be reporting information in the same area. Moreover, at a maximum speed of 25 Km/h for the case of e-scooters in many countries, 100 meters are covered in 15 seconds, time enough to guarantee consecutive transmissions due to LoRa constraints. Upon detecting a vehicle stop, the OBU passes to stand-by mode, switching the subsystems to a low-power state. Moreover, the battery level is periodically monitored, switching to standby if the charging drops under 20% of capacity. This saves energy and preserves it to keep the gas sensors powered and stabilized. In stand-by all other sensors stop their activity, reducing power consumption, and the GNSS receiver is configured in a special low-power mode with periodic wake-ups to reduce acquisition time when needed again. Finally, under this mode, communications are used scarcely to keep alive the connection in the monitoring application.

3.2. Deployment of infrastructure sensors

A set of vehicle detectors have been installed on three streets of Cartagena. Together with a fourth point, which is pending, these sensors allow us to measure traffic flows entering or exiting the city center. This is a milestone in the collection of mobility information since this information will be used to implement sustainable mobility services through real software and simulation tools.

The units mounted are Sky Light Traffic Sensor from Nabla Quadro, which are able to detect vehicles using three complementary approaches: variation in ambient light, detection of objects using active infrared, and magnetic field variation. These are shown in Fig. 3. Vehicles detection for each period configured in the units are reported to our processing infrastructure using the LP-WAN network, since sensors are provided with LoRaWAN communication technology. Thanks to an agreement with the local administration, the sensors have been installed on three key streets in Cartagena, allowing us to monitor traffic entering the city center. Four sensors are installed per street, given that they have two lanes per traffic direction.

Fig 3. Vehicle detectors deployed in the city of Cartagena (Spain)

3.3. Data management and connection with the city hall database

Data collected from our infrastructure, through the LoRa gateway, is received by a LoRa Server. This is a software module implemented with the ChirpStack distribution (https://www.chirpstack.io). Here, a software plug-in has been developed in JavaScript to forward all data to an InfluxDB database (https://www.influxdata.com). This is the base source used by our data analysis and visualization tools.

A set of monitoring panels have been developed with Grafana (https://grafana.com) for a fine-grain study of system operation. Fig. 4 includes one of these panels for the case of one of the vehicle detectors installed near the university campus. Here, traffic density can be checked as well as the basic operation of the sensor in terms of data records received and the status of the communication link. Fig. 4 also shows the panels used to monitor OBUs and the progression of data received from them: PM, atmospheric gas pollutants, noise, weather, and device status.

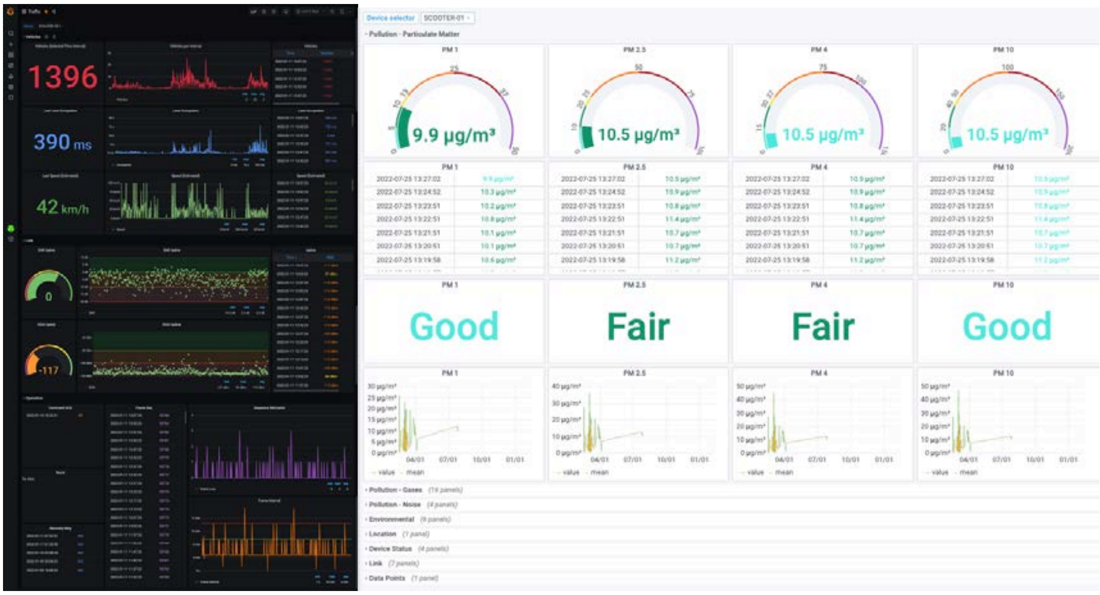


Fig 4. Monitoring panels in Grafana

Although data collection and analysis are carried out in a local server at university premises, hosting Grafana and the Web server, we are synchronized with the city hall smart city infrastructure using Web services. For this, we have developed a data forwarding module that implements a Next Generation Service Interface (NGSI) with the FIWARE infrastructure of the local administration. A proper data model intended to obtain data from environmental sensor nodes has been considered for this.

4. Information processing and web-based applications

4.1. Data analytics and Web-based front end

As indicated above, data is maintained in the InfluxDB database for access for intelligent processing and visualization purposes. The overall architecture of the software developed for this task is shown in Fig. 5. Data coming from OBUs, as well as data received from vehicle detectors, are accessed on the demand by a Web platform developed in Angular (https://angular.io). This application has been provided with extended visualization capabilities, by integrating map visualization tools coming from the mapbox (https://www.mapbox.com). However, the views provided have been enhanced by DECK.GL (https://deck.gl), which adds an extra visualization layer on regular maps with an attractive presentation. All actions from users are processed by our Angular-based engine, which provides a proper visualization. These actions involve the selection of a kind of data to be shown, filters, time windows, and different visualization skins.

When a data prediction is requested for a time window in the future, the Angular engine calls a series of Python-based functions in the back-end that uses machine learning (ML) and time series analysis. Particularly, the scikit-learn (https://scikit-learn.org/) framework is used for base ML algorithms, while SKTIME (https://www.sktime.org/en/stable/index.html) is used for time series analysis. Data collected in the past are considered for fitting models that predict environmental and mobility parameters in the future. This is a tricky part of the software since new models must be created in real-time once a new visualization area is determined within the map. The current operation of the system is satisfactory with past time windows of one year for the case of mobility, which is the largest one, but the application is prepared to constraint the operative fitting datasets to a maximum size, in order to be responsive as the number of users increases.

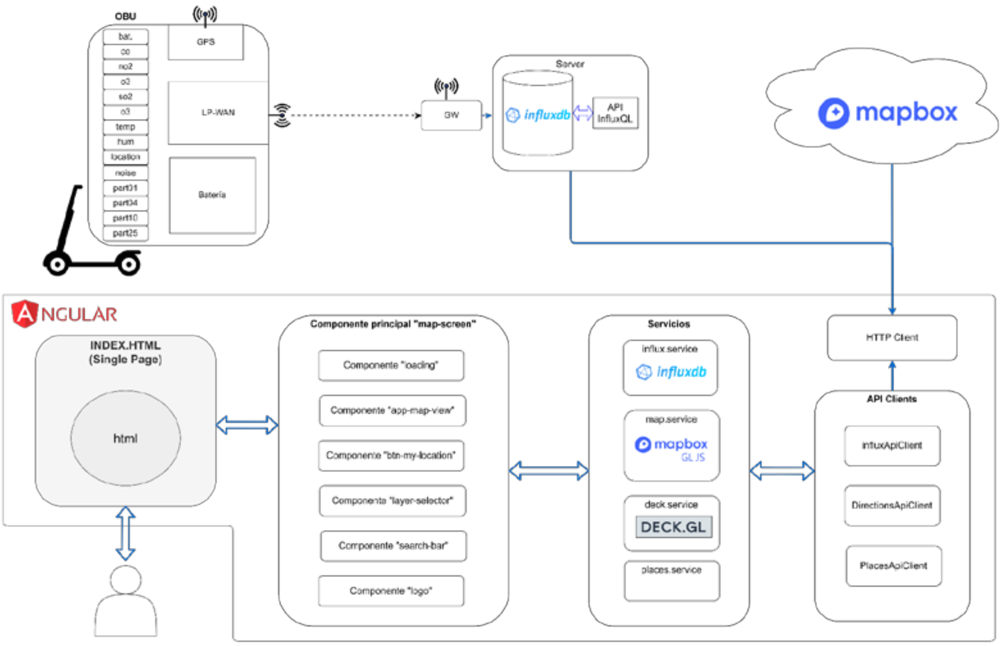


Fig 5. Design of the Web application for data processing and visualization

4.2. Overall validation of the solution

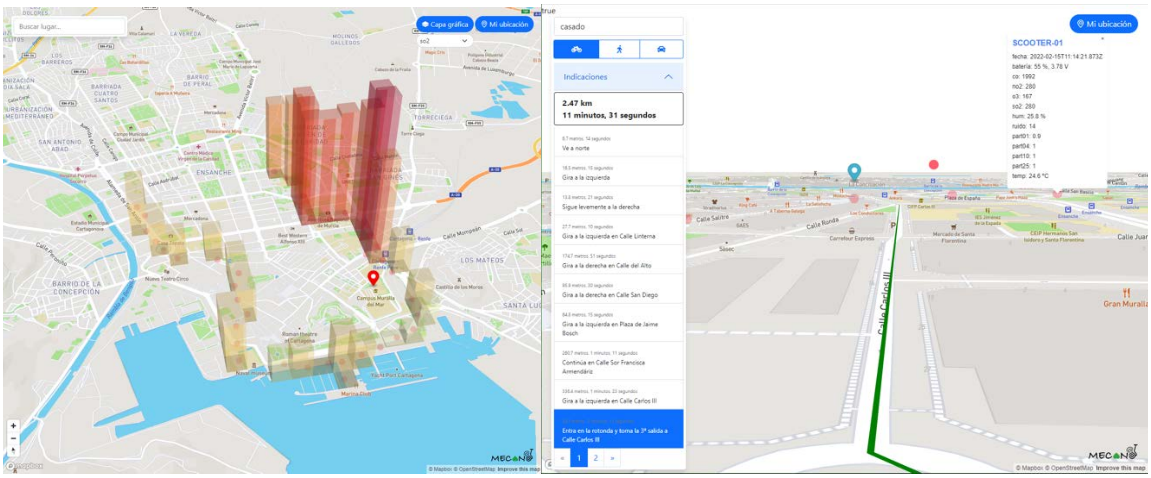
A case study has been developed to validate the solution in urban settings with OBUs on e-scooters moving around the city, collecting and reporting pollution data in real-time, and traffic sensors maintained operative. This serves us to evaluate communications, power consumption, and environmental perception. A LoRaWAN network deployment has been set up spanning the historic center of Cartagena, about 7 Km^2. It is an urban area with narrow streets, high buildings, trees, road furniture, and also three small hills which degrade the 868MHz radio signal propagation. To compensate for this, a LoRaWAN GW MultiTech Conduit IP67 with an outdoor antenna has been installed at 45m above sea level on the roof of the highest and most central university building.

Fig. 6 shows two screenshots of the Web application while running. On the left, it is included a case in which the user is monitoring one of the atmospheric pollutants reported (SO_2). As can be seen, the levels reported are worse in the city center, due to traffic density. Data reported by one of the OBUs connected is visualized here, but other units or pollutants can be chosen. On the right of Fig. 6, it is included a view in which the user is navigating from a source to a target location indicating to avoid polluted areas. In this case, both current and predicted pollution values are considered, given that the travel can take time.

5. Conclusions

A platform for crowdsensing monitoring of environment and mobility using embedded on-board units for personal mobility vehicles and fixed sensors is presented, in terms of design, implementation, and evaluation. The solution is able to gather, monitor and process atmospheric pollution, noise, weather, and traffic density, from mobile and static nodes, by using LoRaWAN communications. Data is managed as a time series database, which is accessed by data analytics software, provided with a front-end visualization system, and a set of data processing modules based on machine learning and time series analysis algorithms. Final services provided include pollution monitoring, vehicle tracking and telemetry, traffic monitoring, and prediction of pollution and mobility factors.

It is a wide effort involving researchers in the area of traffic engineering, telecommunications, electronics, and software engineering, in which there are several on-going and pending works. The most relevant are the evaluation of intelligent processing of data and further identification of the most accurate models, the integration of optimization techniques for improving currently recommended routes, the extrapolation of results in new urban plans in cooperation with the local administration, and the integration of regular vehicle monitoring, as it is on-going in the BREATHE project (https://breathe.upct.es).



true
casado
Indicaciones
2.47 km
11 minutos, 31 segundos
8.7 metros, 14 segundos
Ve a norte
18.5 metros, 15 segundos
Gira a la izquierda
13.8 metros, 21 segundos
Sigue levemente a la derecha
27.7 metros, 10 segundos
Gira a la izquierda en Calle Linterna
174.7 metros, 51 segundos
Gira a la derecha en Calle del Alto
85.9 metros, 30 segundos
Gira a la derecha en Calle San Diego
64.8 metros, 15 segundos
Gira a la izquierda en Plaza de Jaime Bosch
260.7 metros, 1 minutos, 11 segundos
Continúa en Calle Sor Francisca Armendáriz
338.4 metros, 1 minutos, 23 segundos
Gira a la izquierda en Calle Carlos III
Entra en la rotonda y toma la 3ª salida a Calle Carlos III
« 1 2 »

SCOOTER-01
fecha: 2022-02-15T11:14:21.873Z
batería: 55 %, 3.78 V
co: 1992
no2: 280
o3: 167
so2: 280
hum: 25.8 %
ruido: 14
part01: 0.9
part04: 1
part10: 1
part25: 1
temp: 24.6 °C

Fig 6. Screenshots of the Web application developed while monitoring pollution level and planning a urban trip

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