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Monitoring urban environmental phenomena through a wireless distributed sensor network

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Abstract

Purpose – The purpose of this paper is to provide local environmental information to raise community's environmental awareness, as a cornerstone to improve the quality of the built environment. Next to that, it provides environmental information to professionals and academia in the fields of urbanism and urban microclimate, making it available for reuse.

Design/methodology/approach – The wireless sensor network (WSN) consists of sensor platforms deployed at fixed locations in the urban environment, measuring temperature, humidity, noise and air quality. Measurements are transferred to a server via long range wide area network (LoRaWAN). Data are also processed and publicly disseminated via the server. The WSN is made interactive as to increase user involvement, i.e. people who pass by a physical sensor in the city can interact with the sensor platform and request specific environmental data in near real time.

Findings – Microclimate phenomena such as temperature, humidity and air quality can be successfully measured with a WSN. Noise measurements are less suitable to send over LoRaWAN due to high temporal variations.

Research limitations/implications – Further testing and development of the sensor modules is needed to ensure consistent measurements and data quality.

Practical implications – Due to time and budget limitations for the project group, it was not possible to gather reliable data for noise and air quality. Therefore, conclusions on the effect of the measurements on the built environment cannot currently be drawn.

Originality/value – An autonomously working low-cost low-energy WSN gathering near real-time environmental data is successfully deployed. Ensuring data quality of the measurement results is subject for upcoming research.

Keywords Internet of Things, Smart cities, LoRaWAN, Citizen interaction, Distributed sensor network, Environmental phenomena

Paper type Technical paper

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1. Introduction

During Spring 2017, a research project has been carried out by a group of TU Delft students in collaboration with the municipality of Delft and several business stakeholders on the subject of smart cities. The main goal of the project was to acquire evidence of environmental issues in the city centre of Delft by measuring micro-climate indicators. The historic city centre has an irregular layout and a lot of obstacles which provide challenges for some vehicles, especially large buses. That is why the municipality is forced to use old air polluting diesel buses instead of the newer LPG-driven buses, which are not capable to cross the high-arced bridges or some of the tight corner sections. Furthermore, citizens are concerned with the growing number of delivery services on mopeds that are not only a physical hazard, but are also polluting and noisy. Next to gaining information on environmental issues in the city, another goal of the project was engaging citizens of Delft more with research carried out at TU Delft. The project was funded by "Technology Visible in the City". Awareness was raised by the physical sensor platforms and involvement was realized by a Twitter system to communicate with the platforms and by a website providing an overview and the real measurement data. In the future, insight in the data is not only provided to citizens, entrepreneurs and visitors, but institutions will be able to validate and calibrate micro-climate models based on this wireless sensor network (WSN) which will be extended through the historic city and new urban development zones.

Smart city services are often introduced for purposes such as maintenance of historical buildings, waste management, air quality and noise monitoring, traffic congestion, city energy consumption, smart parking, smart lighting and automation of public buildings (Zanella *et al.,* 2014). Technological advancements have reshaped the way technology is used in the built environment and now microcontrollers can be found everywhere, from controlling street lights to monitoring air temperature (Jensen *et al.*, 2016). Sensing technologies to make cities smarter present immense potential for further improving the city (Hancke *et al.,* 2013). Communication also plays a vital role in performing our daily tasks and information is consumed from a wide array of sources. This development can be ascribed to the mass production of electronics, allowing for affordable microcontrollers and sensors, redefining the area of application. New opportunities arise in cities, where the term smart cities is often coined as one of the developments to counter the problems introduced by increased urbanisation. By 2020 it expected that 80 per cent of the European population lives in urban areas (Albino *et al.*, 2015). In general, the smart city concept can be explained as a means to enhance the life quality of citizens (Neirotti *et al.,* 2014).

As an addition to static sensor networks that gather real-time environmental data, the feasibility of implementing a dynamic sensor network based on long range wide area network (LoRaWAN) communication is researched parallel in (Angelova *et al.*, 2018). The emphasis of that research is on the localisation of the sensor platforms. A Wi-Fi fingerprinting radiomap was constructed based on available MAC-addresses, their signal strengths and GPS coordinates. By using GPS for automated radiomap training, the major fingerprinting drawback had been avoided, while limiting the GPS energy consumption still as far as possible.

Taking into account the development of cities into "smart cities" and the use of "Internet of Things" applications in the built environment, the group project focussed on engineering a system that monitors environmental phenomena in the city of Delft. This system will be a low-cost, connected WSN in the city centre of Delft that measures air quality, noise, temperature and humidity. The WSN also provides citizens with actual information about their environment via a web service. This feedback should contribute to raising the citizens' awareness on the importance of environmental health. Moreover, the WSN could help identifying the critical problem areas, in support of urban interventions. Interventions can range from changing the route of a bus as air quality and noise values are expected to cause health issues for citizens, mitigating the urban heat island effect by adding extra greenery or water bodies in the city, and/or changing the layout near a busy road through a city. Therefore, the goals and problem statement are translated in the following research question:

RQ1. How to create a WSN that gathers data on air quality, noise, temperature and humidity and interactively provides the results to the user in order to gain insight in urban health?

The research question is split in the following sub-questions:

RQ1a. Where to install the sensors?

Sensor platforms will be placed at locations within the city centre of Delft that have different profiles. With these different profiles the effects of traffic and urban heat islands can be compared. The sensors should be placed visibly to increase user involvement:

RQ1b. How to build the sensor platforms that measure air quality, noise, temperature and humidity?

Research and experiments have to be conducted on several components of the sensors platforms. This includes the sensors, the microcontroller, the casing and the means of communication of the data:

RQ1c. How to process the environmental data?

The gathered data must be processed on the sensor platform and then sent to a central database in order to be analysed and used:

RQ1d. How to make a WSN interactive?

To create environmental awareness among citizens and to communicate near real-time data the WSN has to be made interactive to engage the users:

RQ1e. How to ensure data quality?

Testing and calibration of the sensors has to be conducted before deployment in order to provide reliable data. Sensor placement might also affect the quality of data.

In the next section, the theoretical framework for this technical paper discussed. Then, in the methodology, the engineering of the system described. The fourth section shows the measurement results of the WSN, followed by a discussion of the results. Finally, the paper concludes by answering the research question and its sub-questions and recommendations for future research.

2. Theoretical framework

Lemmens (1991) defines a geographic information system (GIS) as: "A GIS is an information system containing subsystems for the capture, storage, retrieval, manipulation, analysis and display of spatial data, where each subsystem or combination of subsystems have feedback to an appropriate quality control mechanism". At the input side of this process is the data, the output is the requested information. During the project, the geo-information production process was followed. This process starts with capturing data form the built environment, then pre-processing of the data, followed by analysis and presentation, after which the information can be used for decision making (Lemmens, 1991). Quality control is an important aspect of geographic information (GI) and is part of every component of the GI production process.

In smart environments, data acquisition as well as the first steps of processing is performed through the use of distributed WSNs (DWSN) (Lewis, 2004). With the latest technologies of energy-efficient microcontrollers and wireless communication standards those sensors are often deployed with wireless connections. According to Lewis (2004), different network topologies can be distinguished. For non-interactive sensor networks the star topology is most commonly used, where the sensor stations are all connected to a base station separately. The DWSN deployed for this research follows a three-level tree network topology, where users can connect with individual sensors that are subsequently connected to single hub nodes on the highest level.

Furthermore, in the field of air quality monitoring with low-cost sensor systems there is a need for research on the validation of the quality of sensor data acquired by low-cost sensors (Lewis and Edwards, 2016). Lewis and Edwards (2016) called on researchers to test the accuracy of data originating from the low-cost air quality monitoring devices with well-designed sensor experiments. Cross *et al.*, Castell *et al.* and Mukherjee *et al.* (2017) have conducted research on assessing the performance of those low-cost air quality sensors. They concluded that when implementing a low-cost air monitoring sensor network, one must take account of cross-interferences from other environmental conditions such as temperature, relative humidity, solar radiation, wind speed and wind direction. Moreover, Cross *et al.* and Mead *et al.* (2013) suggested a correction method to apply on the air quality data.

The focus of the project was on making a system that is able to sense phenomena including delivering the results to the citizens. Therefore, the focus was on capturing the data from the built environment, transmitting it via LoRaWAN to the server, analysis and sending the data back to citizens. The quality of the data was not a key aspect in the project and in order to draw conclusions on the reliability of the information, future research is already planned.

3. Methodology

In this section, the engineering decisions with regard to the WSN described: the locations of the sensor platforms, the sensor platforms themselves, processing and transmission of the data, data storage and analysis and the interactive component of the system. The technical system overview (Figure 1) is created in order to illustrate the flow of data from input to output in the geo-information production process of the WSN.

Locations of the sensor platforms

Among the requirements of the municipality were: sensing data on air quality, noise, temperature and humidity in order to acquire evidence of environmental issues in the historic city centre of Delft. Moreover, these data should be disseminated to the users, which also means that the users (e.g. citizens, tourists) should be able to discover the sensor network in the city. Therefore, the locations of the sensor platforms must be chosen in places where environmental issues are likely to occur and locations with sufficient public traffic. Three streets in the city centre are therefore chosen as case study locations: Oude Langendijk, Voldersgracht and Choorstraat.

Oude Langendijk is equipped with two sensor platforms and is characterised by vast amounts of cyclists. Next to that, Oude Langendijk functions as traffic corridor from east to west through the city centre with cars, trucks that supply stores and old diesel buses for public transportation. It is therefore expected that air quality and noise values will be high. Temperature is expected to be lower and humidity higher, since the street contains a high number of trees causing shadows. At Voldersgracht, on the other hand, motorised vehicles are prohibited. Voldersgracht is located next to a narrow canal, containing some tourist shops and restaurants, and is mostly visited by tourists. Voldersgracht is also equipped with two sensor platforms. It is expected that noise values will be high, but temperature values will be lower because of the canal. Finally, Choorstraat is a shopping street that is

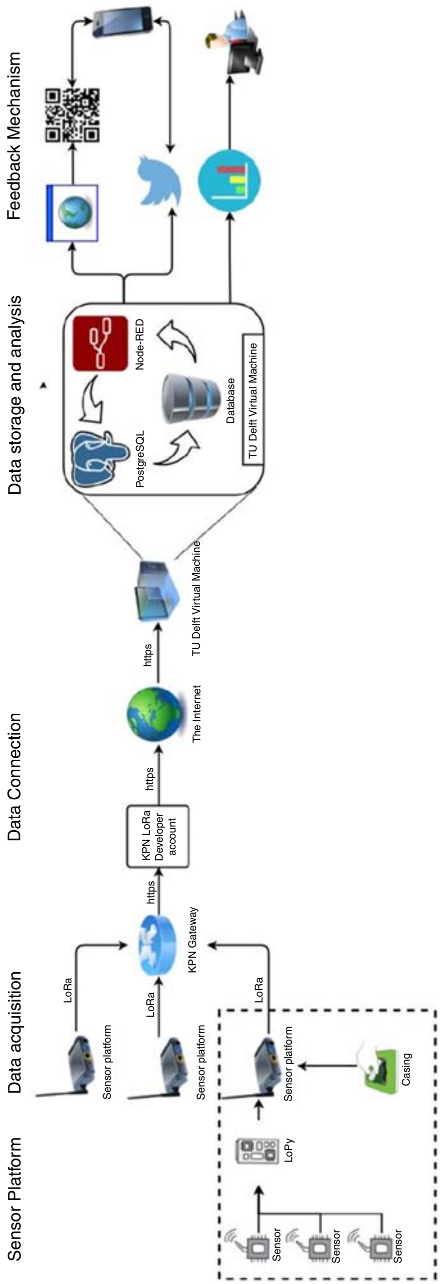

Figure 1.
Technical system overview

also prohibited for vehicles but has no water body next to the street. Choorstraat is chosen in order to act as baseline and is equipped with one sensor platform.

With permission of the municipality of Delft the sensor platforms are placed on trees and lanterns. When there are two sensor platforms deployed in a street (Oude Langendijk and Voldersgracht) they were located relatively close to each other, in order to be able to validate the results of the sensor measurements. Moreover, the sensor platforms are located around 2.5 metres above the ground, i.e. out of reach for people in order to suppress tendencies of theft or vandalism.

Sensor platforms

In order to design a suitable sensor station different hardware is selected and tested. First, a comparative study has been conducted on some of the prevailing microcontroller boards currently available on the market. Based on the project requirements the board should provide ample connection for the various sensors to be connected. Since the sensor platforms will be deployed in public spaces energy consumption is a critical parameter. The platform should also be able to transmit data for which the long range (LoRa) standard is very suitable as it allows small data packets to be sent over relatively large distances while keeping energy consumption low (LoRa Alliance, 2017). The KPN telecom company provides LoRaWAN network coverage on the project locations and free-to-use developer accounts, which is the reason why it is chosen over the community-driven open source The Things Network (TTN). Usage of TTN on the project location would require extra LoRa gateways which is outside the scope of the study. Since the project described is a novel proof-of-concept project some risks are taken regarding the platform maturity. Low-cost is, however, imminent to suit the given budget. Finally, some boards are more suitable to use for integrated solutions, such as sensor platforms. Table I shows the results of the comparative study. The Pycom LoPy development board is chosen because of its energy efficiency and the onboard LoRaWAN interface.

Sensor platforms consist of the LoPy microcontroller, an external LoRa antenna and various sensors, enclosed in a casing together with a power solution. For every environmental data type to investigate within this project there is a sensor attached to the board. For air quality this is the "Plantower" PMS5003 sensor, connected via UART. For measuring global sound the MAX9814 generic microphone used, connected via the OneWire protocol (Maxim Integrated, n.d.). Temperature and humidity is measured with the AM2302 device, connected to the sensor board via I2C (Liu, n.d.). Furthermore, the sensors are powered with an on-board battery and it is possible to attach a solar panel to the sensor platform to increase the autonomous measuring time. For operating and installing the sensor boards additional small electronic components such as RGB LEDs, resistors, transistors, buttons and switches are used.

Board	Energy	Maturity	Interfaces	Capability and integration	Connections	Cost
Pycom LoPy/ ESP32	●●●●●	●	●●●●●	●●●●●	●●●●●	●●●
Raspberry Pi	●	●●●●●	●●●	●●●●	●●●●	●●●
Arduino Uno	●●●●	●●●●●	●●	●●●	●●●●	●●●●
Marvin	●●●●	●●	●●●●	●●●●	●●●●	●●
ESP8266	●●●●●	●●●●	●●●	●●●	●●●●	●●●●●
Custom solution	●●●●●	●●	●●●●●	●●●●●	●●●●●	●

Note: ● more is better

Table I.
Comparative study on available IoT boards

The casings of the sensor platforms consist of an inner and outer component and are made of watertight and corrosion-resistant materials such as acrylic and polypropylene. The inner box includes the microcontroller and battery, while the 3D-printed outer component includes the sensors and antenna. In order to sense the environmental phenomenon properly the outside air has to circulate through the outer casing, therefore the bottom part of the outer component is left open and there is a ventilation hole in the upper part.

Data processing and sending

Scripts on the LoPy for reading sensor values, preparing the data and sending the data over LoRa are written in MicroPython. After the initialisation phase where sensor libraries are loaded and the LoRa connection is set up, an iterative measuring process is started. Temperature, humidity, noise and air quality values are then read after which the data are formatted in a LoRa message payload ready to be sent to a LoRaWAN gateway. Watchdog timers function to detect and recover from malfunctions of the microcontroller. Between the measurement cycles the microcontroller is put in a low-power state to conserve energy.

Data storage and analysis

Data are send to an application server running Node-RED and PostgreSQL. Node-RED is an open-source browser-based flow editing programming interface for connecting Internet of Things devices (JS Foundation, 2017). PostgreSQL is used as an open source object-relational database tool. The Node-RED environment serves as the central location to manage data flows. It retrieves incoming data from the LoRa gateway, decrypts the message, parses the data, and stores it in the PostgreSQL database. When the data are added to the database the record obtains a timestamp. Therefore, the sensed data are near real-time: data are stored in the database 30 s plus the time needed to send over LoRa after it has being sensed.

The interactive component of the system

The goal of providing feedback to users is to raise environmental awareness among citizens: with a WSN as designed for this project citizens can acquire near-real time information on air quality, noise, temperature and humidity data. This information can help citizens in short-term decision making, for example, to include or skip a certain street from their daily jogging route. Or in longer-term decision making, for example, deciding to move to a certain neighbourhood, when the user consulting the information considers personal health important. Therefore, an innovative aspect of the project is the interactivity with citizens and their active involvement. Sensor platforms are placed on lamp posts and trees in the city centre of Delft, physically visible for citizens. Flyers and billboards that are distributed in the area serve to inform passers-by about the project and how to retrieve the results, i.e., by visiting the website via a QR-code or by sending a data request to a server via Twitter. The website contains information on the project in general, news and a dashboard with the latest readings of the sensors and time series of the data coordinated per street.

Node-RED is used to create the Twitterbot which contains the feedback mechanism. Moreover, Node-RED is used to setup the data dashboard to show data to citizens via the website. For both the Twitterbot and the dashboard, Node-RED retrieves data from the database and flows it to the correct application.

4. Results

Measurements in the built environment have been done for five days, since the project group was constrained by time limits. During the measurements the batteries would sometimes have to be replaced. To investigate the values of environmental phenomena in relation with the built environment by using such a WSN, the time span of measuring should be much longer in order to get redundancy in the data set. The environments of the different sensors present varying effects on the measurements. For more local analyses of temperature and humidity and the other phenomena the reader is referred to the project report available on the website of the Geomatics programme[1].

Temperature and humidity measurements

Figure 3 shows the results of, respectively, the temperature and humidity values on the five measuring locations, over a time span of 48 h (Figure 2).

After the measuring period the measured environmental phenomena in the streets showed local differences in humidity and temperature. These differences can be accredited to the fact that some streets received more sun than others. For example, the two sensor platforms in Oude Langendijk have the lowest temperatures and highest humidity values, which is logical since the vast amount of trees that are located close by.

Noise measurements

Noise levels had no viable measuring results due to the restrictions in software, communication interface and the type of sensor. For a phenomenon that is as variable as noise levels in a city, a single noise value sensed only once in 15 min is insufficient. At least statistics such as median, mean, minimum and maximum should be added. However, then the communication over LoRa would introduce a bottleneck since only small messages with a maximum number of 54 bytes can be send over LoRa with KPN (2017). TTN that also provides LoRa will be inappropriate for the same reason. In general, LoRaWAN is insufficient for real-time applications that always need to be connected (Adelantado *et al.*, 2017). Moreover, the MAX9814 is a microphone with automatic gain control (AGC) that automatically lowers the output value depending on the height and duration of the input. Therefore, the AGC of this device should be modified.

When a communication protocol that allows bigger message payloads to be sent is used, i.e., measuring results of every 30 s, the MAX9814 can send valuable information. Figure 3 shows results of a test with MAX9814 microphones at four different locations and it includes some observations during the tests.

Air quality measurements

Similarly, to the sound sensor, the results for the PMS5003 sensor would also be more representative when a shorter interval is used, e.g., 30 s. Then data for a graph like the one in Figure 4 can be sent, where the first peak represents cigarette smoke close to the sensor and the second peak represents the emission of a car from very close-by. In order to draw conclusions on the existence of a link between the characteristics of a certain street and the local air quality, the measurements should be done over a longer time span.

5. Conclusions of the pilot project

The question "how to create a wireless sensor network that gathers data on air quality, noise, temperature and humidity and provides the results to the user?" can be partially answered by looking at individual sub-questions.

First of all, the locations of the sensor platforms should be visited by many citizens and tourists, to ensure a significant amount of people can be reached. Likewise, the different areas of interest should have different patterns and environments to detect differences if present. Therefore, the Voldersgracht, Oude Langendijk and Choorstraat are good locations to place the sensors. The location of the sensors in these streets should be out of reach to prevent vandalism but also visible to support interactivity. For future research it is

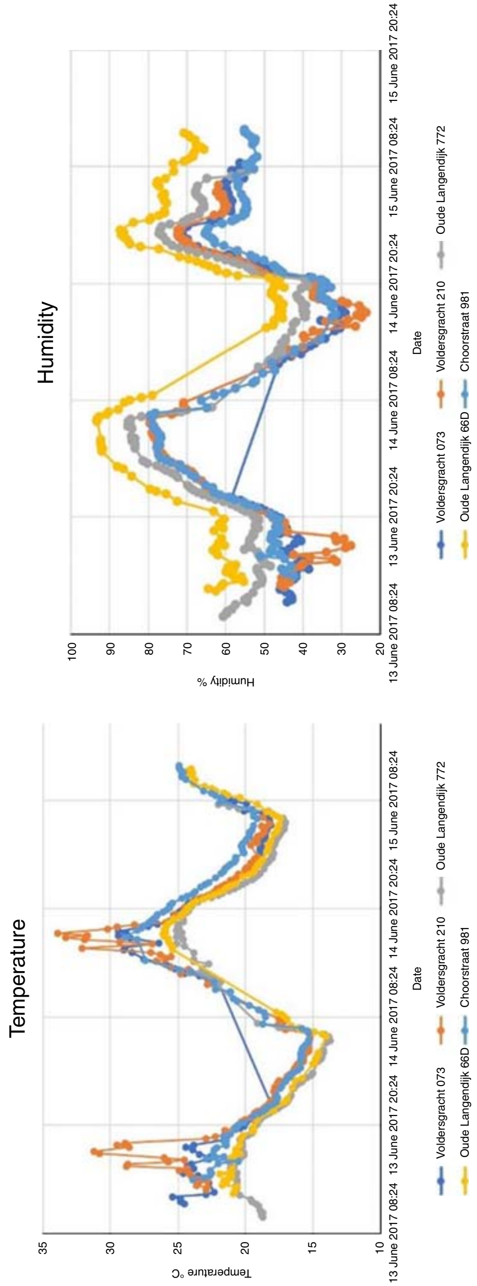

Figure 2.
Temperature and humidity measurement results

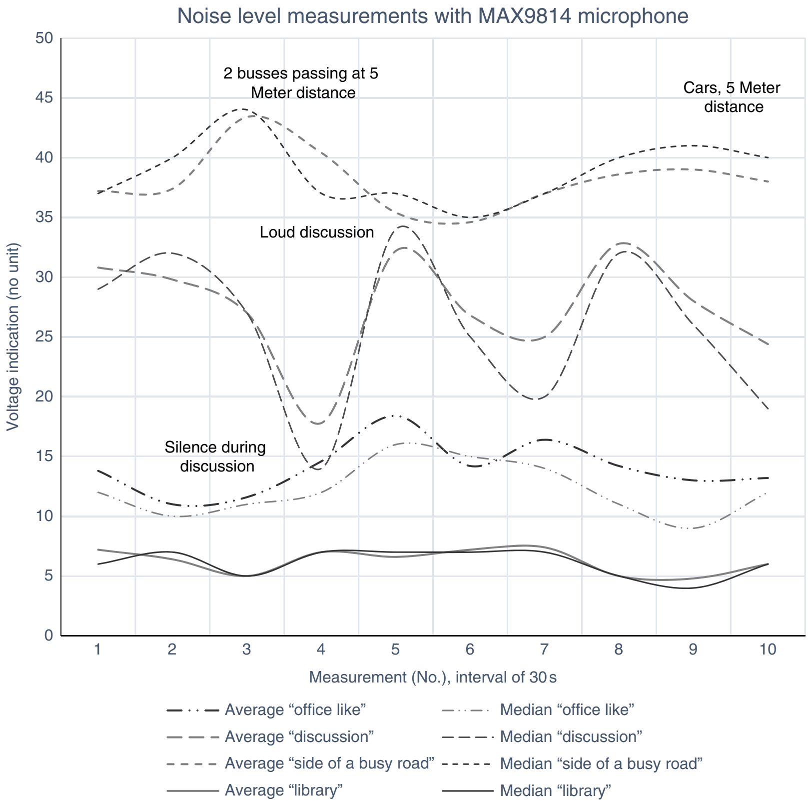

Figure 3. Extra tests with MAX9814 microphone/noise sensor

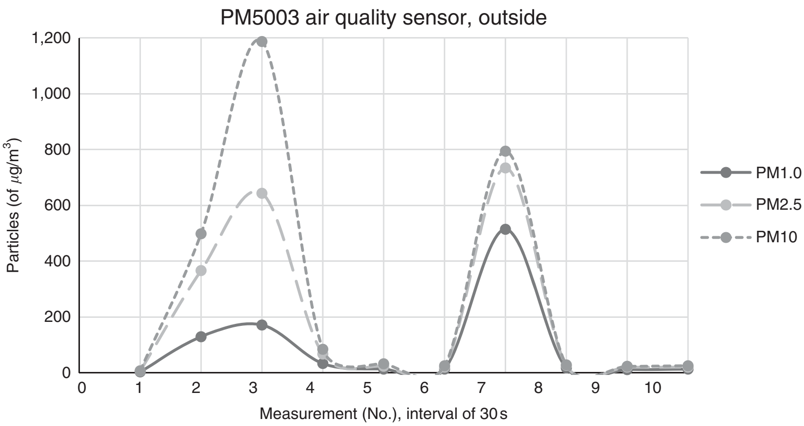

Figure 4. Extra tests with PMS5003 air quality sensor

important to take into account that direct sunlight or solar gain has a big influence on the measured temperature.

Creating a sensor platform starts with deciding on which sensors and other hardware are suitable to use. After this the code has to be written that will collect the data through the sensors. Then, a design has to be made for casing and this one has to be build. At last the different elements of hardware and software should be combined and deployed.

Then, after sensing the data, pre-processing the data on the LoPy microcontroller and then sending over LoRa, the data are processed by generating graphs and metadata like mean, minimum and maximum values.

How to turn a WSN into an interactive system was an important aim during the project. As one of the goals of the project was to connect with the citizens of Delft they had to feel connected to the data. The best way to connect with the data is to interact with the data. In order to interact several social media platforms as well as offline strategies have been identified as potential candidates. As the data are mainly in digital form, the offline strategies were discarded in favour of social media. Due to the ease-of-use and suitability Twitter has been chosen as the platform to connect interactively with the citizens. The created Twitterbot can automatically reply with the requested sensor data. Furthermore, live data can be explored on the accompanying website[2]. To make sure the target group is aware of this interactivity a media outreach is done including Facebook, billboards, flyers and articles in local newspapers.

Finally, ensuring data quality is important to draw reliable conclusions. At first the sensors themselves need to be reliable and of good quality. Results have shown that especially with inexpensive sensors individual differences may be found in the different sensors. Calibration therefore has to be done in a stable environment together with the training sensors. After this, being critical on the data output is very important; outliers, systematic errors or decay of hardware are still possible.

6. Outlook

By combining the latest hardware and communication technology, the pilot study has provided valuable information about the potential of WSNs for citizens. Some of the initial goals of the project were not met in the desired time span, e.g., reliably determining air quality and noise level values. The project is to be continued next year with the goal of maturing the sensor platforms and streamlining the assembly of new sensor platforms. With the shown potential it is possibly more enticing for citizens to participate in crowd sensing and to become part of future initiatives. In parallel, research projects are running on the positioning of users by Wi-Fi and improving the data quality of sensors. The quality of the sensors can be investigated further by enlarging the time span of the measurements and cross-validating the results from different sensors. Moreover, the scale of the project and research can be increased to make measurements for the whole city, for example, by using a dynamic sensor network. This can be done by equipping moving vehicles with sensor platforms instead of having them on fixed locations. Next to that, research on the current state of environmental awareness (*ex ante*) of citizens could be done in order to be able to observe a change of their environmental awareness that might be caused by the environmental information provided to citizens via a WSN (*ex post*). Subsequently, the usefulness of this type of near-real time environmental data for citizens should be researched. Finally, comparing different city centres of different cities can also result in interesting findings about the environmental issues of the cities.

Notes

1. Available at: www.tudelft.nl/en/education/programmes/masters/geomatics/msc-geomatics/programme/synthesis-project/
2. Available at: www.scdelft.nl/

References

Adelantado, F., Vilajosana, X., Tuset-Peiro, P., Martinez, B., Melia-Segui, J. and Watteyne, T. (2017), "Understanding the limits of LoRaWAN", *IEEE Communications Magazine*, Vol. 55 No. 9, pp. 34-40, available at: https://doi.org/10.1109/MCOM.2017.1600613

Albino, V., Berardi, U. and Dangelico, R.M. (2015), "Smart cities: definitions, dimensions, performance, and initiatives", *Journal of Urban Technology*, Vol. 22 No. 1, pp. 1-19, available at: https://doi.org/10.1080/10630732.2014.942092

Angelova, L., Flikweert, P., Karydakis, P., Kersbergen, D., Teeuwen, R., Valečkaitė, K., Verbree, E., Meijers, M. and van der Spek, S. (2018), "Using a dynamic sensor network to obtain spatiotemporal data in an urban environment", *Adjunct Proceedings of the 14th International Conference on Location Based Services*, pp. 13-18.

Hancke, G.P., de Silva, B.C. and Hancke, G.P. (2013), "The role of advanced sensing in smart cities", *Sensors*, Vol. 13, pp. 393-425, available at: https://doi.org/10.3390/s130100393

Jensen, C.D., Marchiori, A. and Gerstle, N. (2016), "Engineering sensor networks for energy studies of the built environment", *Environmental Progress & Sustainable Energy*, Vol. 36 No. 2, pp. 539-547, available at: https://doi.org/10.1002/ep.12497

JS Foundation (2017), "Node-RED", available at: https://nodered.org/about

KPN (2017), "LoRa forum: frequently asked questions", available at: https://zakelijkforum.kpn.com/lora-forum-16/frequently-asked-questions-faq-8329

Lemmens, M.J.P.M. (1991), "GIS: the data problem", *European Conference on Geographical Information Systems*, pp. 626-636.

Lewis, A. and Edwards, P. (2016), "Validate personal air-pollution sensors", *Nature*, Vol. 535 No. 7610, pp. 29-31, available at: https://doi.org/10.1038/535029a

Lewis, F.L. (2004), "Wireless sensor networks", in Cook, D.J. and Das, S.K. (Eds), *Smart Environments: Technologies, Protocols, and Applications*, John Wiley, New York, NY.

Liu, T. (n.d.), "Digital-output relative humidity & temperature sensor/module", available at: www.sparkfun.com/datasheets/Sensors/Temperature/DHT22.pdf

LoRa Alliance (2017), "LoRa Alliance™ technology", available at: www.lora-alliance.org/what-is-lora

Maxim Integrated (n.d.), "MAX9814", available at: https://datasheets.maximintegrated.com/en/ds/MAX9814.pdf

Mead, M.I., Popoola, O.A.M., Stewart, G.B., Landshoff, P., Calleja, M., Hayes, M., Baldovi, J.J., McLeod, M.W., Hodgson, T.F., Dicks, J., Lewis, A., Cohen, J., Baron, R., Saffell, J.R. and Jones, R.L. (2013), "The use of electrochemical sensors for monitoring urban air quality in low-cost, high-density networks", *Atmospheric Environment*, Vol. 70, pp. 186-203, available at: https://doi.org/10.1016/j.atmosenv.2012.11.060

Mukherjee, A., Stanton, L.G., Graham, A.R. and Roberts, P.T. (2017), "Assessing the utility of low-cost particulate matter sensors over a 12-week period in the Cuyama valley of California", *Sensors*, Vol. 17 No. 8, p. 1805, available at: https://doi.org/10.3390/s17081805

Neirotti, P., De Marco, A., Cagliano, A.C., Mangano, G. and Scorrano, F. (2014), "Current trends in smart city initiatives: some stylised facts", *Cities*, Vol. 38, pp. 25-36, available at: https://doi.org/10.1016/j.cities.2013.12.010.

Zanella, A., Bui, N., Castellani, A., Vangelista, L. and Zorzi, M. (2014), "Internet of things for smart cities", *IEEE Internet of Things Journal*, Vol. 1 No. 1, pp. 22-32, available at: https://doi.org/10.1109/JIOT.2014.2306328.

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