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Authors:

Luca Lombardo
Dipartimento di Elettronica e Telecomunicazioni, Politecnico di Torino, Torino, Italy

Marco Parvis
Dipartimento di Elettronica e Telecomunicazioni, Politecnico di Torino, Torino, Italy

Francesco Vitiello
Dipartimento di Elettronica e Telecomunicazioni, Politecnico di Torino, Torino, Italy

Emma Angelini
Dipartimento di Scienza Applicata e Technologia, Politecnico di Torino, Torino, Italy

Sabrina Grassini
Dipartimento di Scienza Applicata e Technologia, Politecnico di Torino, Torino, Italy

DOI: 10.1109/MeMeA.2018.8438701

A Sensor Network for Particulate Distribution Estimation

Luca Lombardo,
Marco Parvis,
Francesco Vitiello
Dipartimento di Elettronica e Telecomunicazioni
Politecnico di Torino
Torino, ITALY
Email: luca.lombardo@polito.it

Emma Angelini,
Sabrina Grassini
Dipartimento di Scienza Applicata e Tecnologia
Politecnico di Torino
Torino, ITALY
Email: sabrina.grassini@polito.it

***Abstract*—This paper describes the development of a sensor network designed to estimate the spatial and temporal distribution of particulate in the air. The network employs sensor nodes which are based on an optical solution and are capable of estimating the particulate size distribution. The sensor nodes employ a commercial fiberglass filter through which the air is forced to pass by means of a small pump. A video camera coupled to an inexpensive RaspberryPI Zero W is used to acquire and process the filter image. A small LoRa wireless module is coupled to the the RaspberryPI in order to transmit the acquired data over a range exceeding 10 km. The nodes can measure reliably particles down to sizes of 10 μm, usually refereed to as PM10 and a solution down to 2.5 μm, (PM2.5) is being tested. The fiberglass filter is in form of a strip and a small motor is used to move the strip and to start a new measurement when the filter gets covered in dust. The overall node cost is of less than 100$.**

***Index Terms*—Human health, Distributed Particulate Measurement, Environmental monitoring, Air pollution**

I. INTRODUCTION

The atmospheric particulate matter is a complex mixture of small particles suspended in the air. The particles, which size ranges from hundreds of micrometers down to few nanometers, can have different chemical composition and structure. Nowadays, atmospheric particulate matter represents one of the most dangerous pollutants, especially in large cities and industrial areas. The inhalation of particulate by humans is considered very harmful for health: particulate can enter lung alveoli producing allergies, a reduction of breath capability and, when the size is lower than 2.5 μm [1,2], it can enter the tissues and accumulate with very dangerous consequences also for cardiovascular system. The correlation between the onset of respiratory and cardiovascular diseases has been notably highlighted [3] and the World Health Organization (WHO) has estimated in about two millions the deaths due to atmospheric particulate pollution [4,5].

In order to assess the health risk correlated to the exposure of unsafe levels of atmospheric particulate matter it is compulsory to measure the actual concentration of the particulate matter and its size distribution, especially in highly populated areas. In this framework, a low cost alternative to conventional commercial systems for particulate monitoring can be of great interest and the possibility to arrange a monitoring grid able to effectively provide real-time and reliable information on the pollution level can be helpful to improve life conditions of people in high-polluted cities.

Usually commercial sensors are designed to measure only a specific particle size and are refereed to as sensor for $PMxx$ particulate, i.e. sensors labeled as $PM10$ means that they are designed to measure 10 μm particles and so on. Most of these sensors are based on passive filters that stop particles which size is larger than the targeted dimensions. This way, only particles having dimension smaller than the rated are effectively collected and measured.

Sensors can be designed according to different principles [1,6,7] but often they are not able to estimate the amount of particles having different sizes. On the other side, being the health effects strictly correlated to particulate size, it would be quite interesting to have sensors capable of providing this information. This kind of sensors, however, have been proposed only to estimate the size distribution of very small particles [8].

Furthermore, in most cases commercial sensors are quite big and expensive so that it is impossible to arrange a pervasive sampling of the particulate on a large scale. Usually, measurements are only performed in few locations and the obtained values are not representative of the real distribution of the particulate in a given region, because most of the heavy particles fall to ground not far from the place where they are produced by any polluting activity.

In this paper the authors describe a simple approach which is based on a network of low cost sensors which should be suitable to answer all these problems providing a measurements of the particle size distribution in several points thanks to a network architecture coupled with low-cost wireless devices. The proposed solution takes advantage of the standard LoRa protocol [15], which is an evolution suitable for long distances and limited transmission rates.

II. THE GRID ARCHITECTURE

Connecting together many sensor nodes to arrange a sensor network grid can be obtained by using several different principles [9]–[12]. Some of them are specifically designed for low power applications, but can cover only short distances; others employ the commercial cellular network to reach longer distances, but at the price of an expensive subscription. LoRa protocol instead does not require a subscription and can reach long distances although at the price of a low connectivity speed. LoRa is the acronym for Long Range connectivity [15] and is a protocol which is specifically designed for low-power battery operated architectures arranged in a start-of-starts topology with typical ranges of 10 km. LoRa is gaining more and more popularity [10,14] and can be used with quite limited effort thanks to the commercial availability of low cost connection boards and modules.

Fig. 1 shows the proposed architecture, which is based on several LoRa equipped nodes based on the RaspberryPI Zero W, one or more LoRa concentrators and a distributed cloud storage, which allows accessing the measurements from everywhere. The figure shows:

- The LoRa nodes. These are the sensing nodes, which are based on the RaspberryPI Zero W, a small and cheap PC on single board supporting both WiFi and Bluetooth. A small video camera is used for the measurements and a low-cost LoRa module insures the connectivity of the node. Many nodes can be arranged and connected by LoRa protocol according to the star-to-stars topology.
- The LoRa concentrators. These components receive data from the measuring nodes located in the same city, within some kilometers and routes them to the network storage thought the Internet. Concentrators are basically sensing nodes without the measurement hardware and take advantage from the RaspberryPI WiFi support for connecting to the Internet.
- The network based storage. This is the core component of the grid architecture which receives data from all the nodes, stores and makes them available to the users. The Network Storage is composed of three main components: the Access Control Manager (ACM), the Access Data Router (ADR) and the Storage Unit (SU).
  - The ACM is designed to control user access, granting only identified users to access and read specific data. The ACM also checks the received data before accepting them to avoid data spoofing. It is also designed to export some Application Program Interfaces (APIs) which can be used to let users to register and receive push notifications when some of the data reach specific programmable threshold levels. This way, it is possible to deliver real time alarms to specific user mobile devices.
  - The Access Data Router represents the bridge between users and data; it is able to arrange http pages to be sent on request to specific users after they identify themselves.
  - The Storage Unit is composed of a commercial cloud infrastructure. The data safety is in this case obtained by encryption of all data stored on the cloud itself.
- The phone-based (real-time client) and the PC-based clients, provided with dedicated applications, allow final user to remotely access measured data, analyze and export them in several formats.

III. The measurement node Architecture

The sampling node is able to optically detect the atmospheric particulate matter and estimating the single particle size in order to achieve the particulate size distribution. Basically, a small pump forces a specified air flow on a sampling glass-fiber filter where particulate is captured. Periodically, a camera system takes photo of the filter surface and a specifically designed software, running on the RaspberryPI Zero W provides to detect the particles. The block diagram of the system is shown in fig. 2, where the main system components are:

- A small low-power air pump. The pump is employed to force a specified flow of air from the external environment through a sampling filter. The pump is controlled by the RaspberryPI Zero W using a power interface in order to achieve an air flow in the range between 0.1 L/min and 0.2 L/min. The air flow can be chosen according to the pollution level in order to obtain a good trade off between filter life and system sensibility. The pump is mounted downstream of the filter, so that any possible contamination is avoided.
- A commercially-available glass-fiber filter strip capable of stopping particles from the air flux. The filter is available with several different meshes down to 1 μm.
- A moving system for the filter. This system moves the filter when its surface becomes saturated by particulate. It is realized by a stepper motor, a dedicated driver and a mechanical system completely manufactured using a 3D printer. The stepper motor, interfaced by the driver, is controlled by the RaspberryPI Zero W using General Purpose IO lines.
- A collecting chamber has been manufactured in PLA by using a 3D printer. The chamber shape has been designed in order to allow the filter tape to be easy replaced and, at the same time, it guarantees an almost uniform air flux all over the exposed surface of the filter. A mask on the exposed filter surface is used to define the deposition area.
- A backlighting system. The back-light is used to back-illuminate the filter so that the front camera can take pictures of the filter surface. This way, captured particles appear as dark blobs on a partially white background. The system employs an IR LED (880 nm), an RGB LED (625 nm, 528 nm, 470 nm) and an UV LED (375 nm) as light sources. These LEDs can be individually turned on by the RaspberryPI Zero W so that it is possible to implement a simple spectral analysis of the particulate.
- A cheap digital camera (Raspberry PI NoIR Camera V2). This is the sensing element of the system: it periodically takes photo of a small area of the filter surface in order to detect the captured particulate. The camera has a resolution of 8 Mpixels (3280×2464 pixels) and a

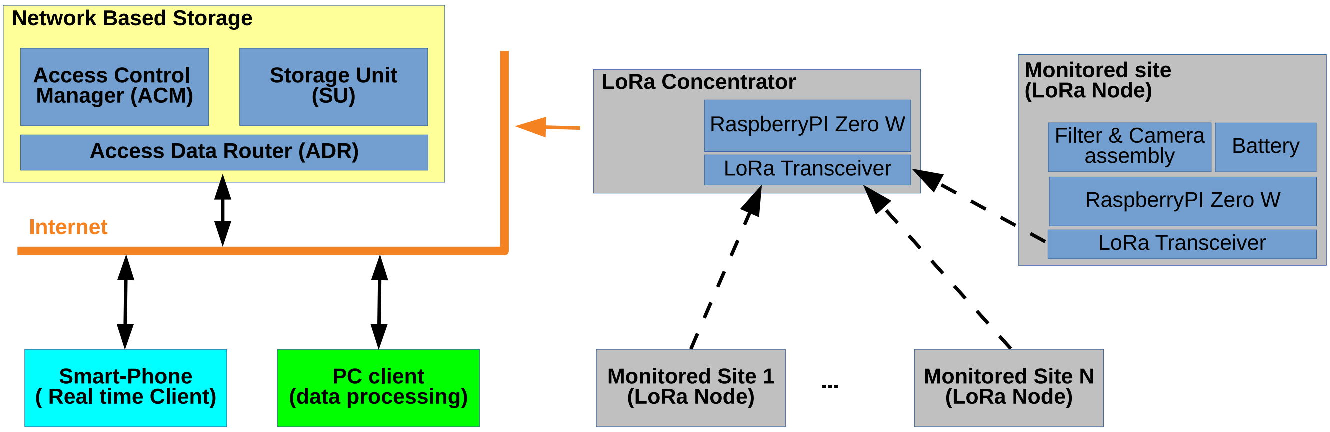

Fig. 1. Block diagram of the measuring grid architecture which is composed of nodes employing the LoRa wireless connection system.

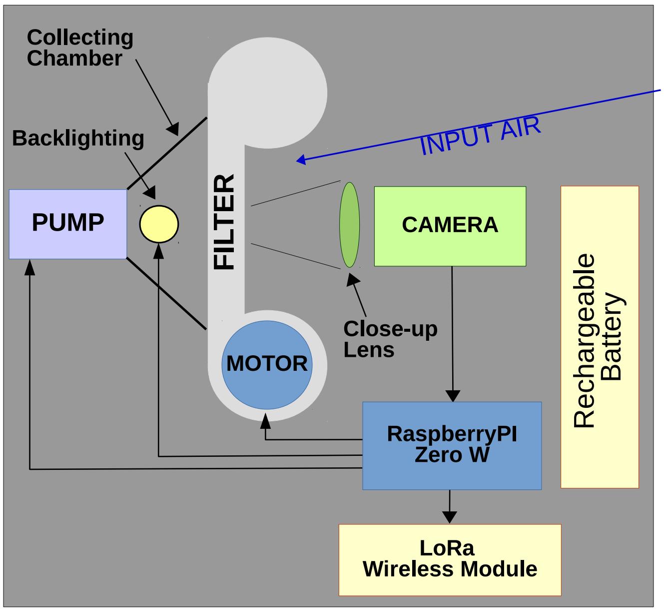

Fig. 2. Block diagram of the measuring node which is based on a RaspberryPI Zero W, a small commercial camera, and a LoRa transceiver.

manual focus using a single lens. In order to achieve the required resolution and magnification for the particulate detection an additional macro lens has been added on a 3D printed support. The macro lens is a commercial lens for smart-phones with a magnification of $15\times$. The camera focusing is performed only once at system calibration. The camera is connected to the RaspberryPI Zero W using the dedicated flat cable over the Camera Serial Interface (CSI). With the employed optical system the instrument reaches an effective resolution of about $2\ \mu\mathrm{m}/\mathrm{pixel}$.

- A RaspberryPI Zero W. The RaspberryPI is a small and cheap computer on single board featuring a 32-bit $1\ \mathrm{GHz}$ ARM microprocessor, $512\ \mathrm{MB}$ of RAM and it is able to run high-level operating systems, like many Linux distributions. It manages all the operations required in order to perform the measurements: control the pump, the backlighting, the filter tape movement system, the camera and transmit acquired data using the LoRa protocol. The RaspberryPI also performs all the image processing in order to detect the particulate and estimate its size.
- The LoRa Wireless module $RN2483A$. The module, manufactured by Microchip, implements all the LoRa Stack and it is interfaced to the Raspberry PI Zero W using the UART interface. The module is employed to connect each single sensing node to the LoRa Concentrators over a typical range af some kilometers.
- A rechargeable battery, intended to power the whole node. The battery can be recharged with either an external standard power supply or a dedicated solar panel. An operative life of about one week can be easily obtained selecting a battery with a capacity of $20\ \mathrm{Ah}$.

Fig. 3 shows an example of the realized prototype.

IV. The Node Software

The software running on the RaspberryPI Zero W controls the node hardware, acquires pictures of the filter surface and processes them for detecting the captured particulate, and interfaces the node to the LoRa network enabling remote control and data transmission. Even though several different solutions have been proposed which employs quite different algorithms [16,17], the author decides to use a quite simple algorithm which takes advantage of open-source libraries. All the software is written in Python programming language and emplys the openCV library [18] for the image processing.

LoRa concentrators do not employ the image processing and the hardware control software, but they use the LoRa Interface and are able to connect to the Internet through the WiFi in order to upload data of all the connected nodes. Furthermore, they implement a remote interface for remotely control and program each single node and retrieve all the acquired data.

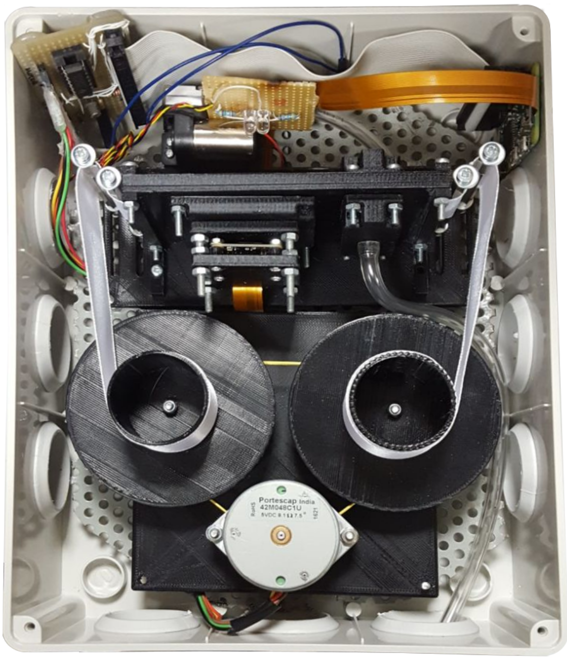

Fig. 3. The first prototype of the realized measuring node.

A. The Image Processing Software

The image processing software acquires the images of the filter surface using the PyCamera module. The acquired images are then processed in order to identify the particulate on the surface and to estimate its equivalent size according to a four step algorithm:

- The captured image is converted into grey-scale mode. This is accomplished according to the back-lighting source used for taking the pictures. In particular, red and blue channels are selected respectively for IR and UV back-lighting, single red, green and blue channels are used for each one of the RGB LEDs. Instead, when multiple LEDSs are used at the same time grey-scale conversion is performed according to the equation:

$$G = \sqrt{R^2 + G^2 + B^2} \tag{1}$$

- A selective gaussian blurring is applied to the grey-scale image in order to reduce the effects of the background filter fibers without impairing the recognition of the particles.
- A 2D kernel filtering is applied in order to increase sharpness of the image. The kernel K has a size of 5×5:

$$K = \begin{bmatrix} K_0 & K_0 & K_0 & K_0 & K_0 \\ K_0 & K_1 & K_1 & K_1 & K_0 \\ K_0 & K_1 & K_2 & K_1 & K_0 \\ K_0 & K_1 & K_1 & K_1 & K_0 \\ K_0 & K_0 & K_0 & K_0 & K_0 \end{bmatrix} \tag{2}$$

  and the selection of the parameters K_0, K_1 and K_2 is crucial for obtaining a good performance from the blob detection algorithm.
- A blob detection algorithm is applied. The algorithm is based on a progressive threshold binary matching. The algorithm is able to perform a filtering of the detected particles according to their features like size, circularity and shape.

The parameters used in the image processing have to be selected during the calibration of the measurement system.

B. Remote Interface Software

The remote interface software allows users to control each single sensing node and to retrieve the acquired data. It is written in Python and it provides a remote Graphical User Interface (GUI) with four different tabs: Dashboard, Automatic Operation, Manual Operation, Data Analysis.

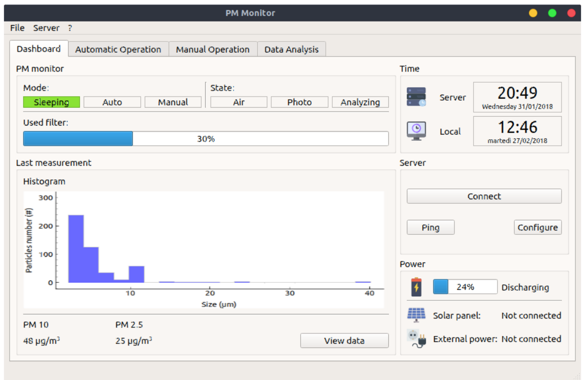

Fig. 4. Screen shot of the Dashboard Tab, where the main controls of the system (as the server connection, the filter status and last acquired data) can be accessed.

- The Dashboard Tab contains the main controls useful to access the actual state of the node. Here it is possible to connect the server, visualize the filter status, the last data acquired, the working mode and the status of the battery. Fig. 4 shows the Dashboard interface with all its controls.
- The Automatic Operation Tab permits to configure each node to operate autonomously. It is possible to set individually for each day of the week the starting and stopping time of the sampling.
- The Manual Operation Tab permits to individually turn on/off each single hardware part, like the stepper for the filter tape, the back-lighting LEDs, the air pump and the camera.

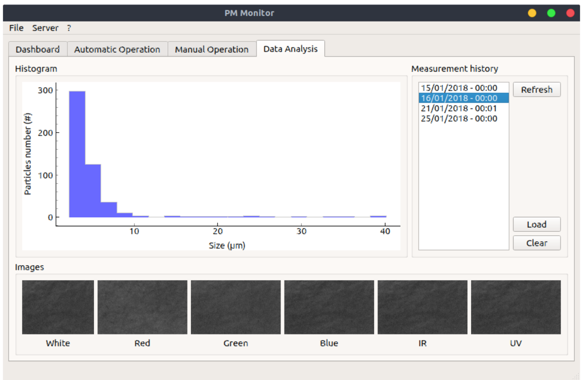

Fig. 5. Screen shot of the Data Analysis Tab, where all the acquired photos and processed data are available .

- The Data Analysis Tab, instead, aggregates all the acquired photo of the filter and the measured particulate values. All the photo at the different wavelengths are available for processing and for each of them it is possible to visualize the histogram of the particulate size distribution. In fig. 5 is visible the tab with the controls for accessing taken pictures and estimated data.

V. Result and Discussion

Some preliminary measurements of atmospheric particulate matter have been already carried out in North of Italy. Measurements have been acquired under real conditions placing the proposed system on the side of a quite busy road in Turin. Sampling time was $20\ \mathrm{h}$ with an air flux of $150\ \mathrm{mL/min}$. The selected filter is a commercial $GF10$ borosilicate fiber glass filter tape with an average porosity of $3\ \mu\mathrm{m}$ and a thickness of $350\ \mu\mathrm{m}$. The particulate capturing area was $15\ \mathrm{mm} \times 15\ \mathrm{mm}$, while the analyzed area was $1.4\ \mathrm{mm}\ \times\ 1.4\ \mathrm{mm}$. The results of the measurement taken in a polluted city of North of Italy are reported in Fig. 6. The figure shows picture of the filter as taken by the camera (a) and the map created by the recognition software (b). From this data the software creates the histogram of the particulate size distribution, that is reported in fig. 7. The peak of particle size distribution is at $5\ \mu\mathrm{m}$ and a secondary peak is centered at $9\ \mu\mathrm{m}$.

VI. Conclusions

Commercial systems currently available on the market are usually capable to measure atmospheric particulate matter only for fixed and well defined particle sizes. Moreover, generally they are quite expensive, and this prevents the possibility to arrange pervasive monitoring networks over large areas. The proposed system is quite cheap and is able to estimate the particulate size distribution in quasi real-time. It is also quite small and provide a wide range wireless connectivity. Thanks to the embedded LoRa wireless protocol, it is easy to arrange an effective sensing network for particulate monitoring even on large scale, like cities or industrial areas featuring a very large number of sensing points.

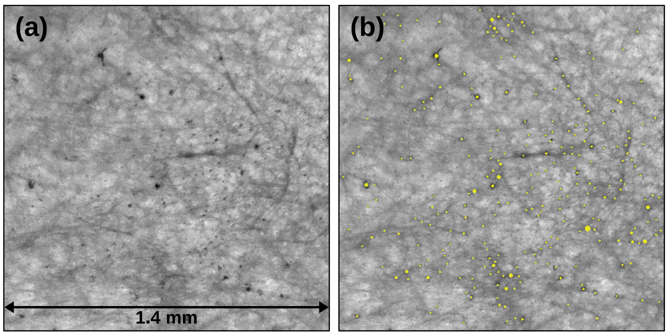

Fig. 6. Picture of the exposed filter as taken by the camera (a) and particulate map created by the detection software (b).

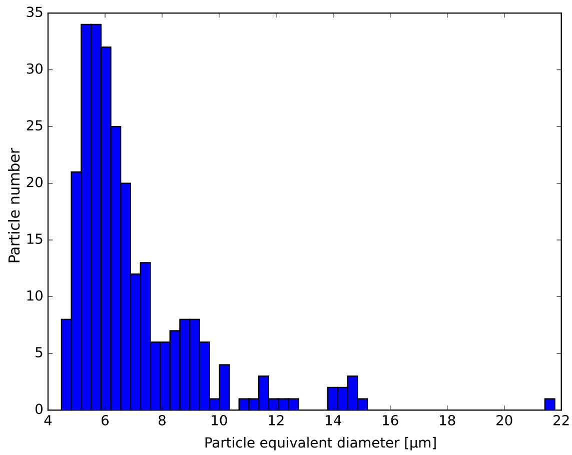

Fig. 7. Histogram reporting the particle size distribution as detected by the software. The peak of particle distribution is at a size of $5\ \mu\mathrm{m}$ and a secondary peak is centered at $9\ \mu\mathrm{m}$.

Even though the development of sampling system is still in progress, the first measurements acquired with the realized prototype looks very promising and further measurements have been already scheduled for better evaluating the performance of the system. Several hardware improvements need to be performed in order to reduce the overall size of the system and minimize the power consumption in order to increase the operative life under battery operation. Moreover, some improvements of the optics and of the detection software can be adopted in order to increase the detection reliability and to simplify the selection of the software parameters that are crucial for the performance of the system.

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