A mobile measurement system for urban pollution monitoring

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Abstract: The paper proposes a mobile measurement system for urban pollution monitoring that can be installed on public ground transportation vehicles. It exhibits some important features that make it suitable for the purpose: low cost, reduced dimensions, autonomous power supply, and measurement strategy able to minimize the measurement uncertainty. To this aim, the measurement system implements data fusion techniques that operate spatial and time data integration. The general architecture of the proposed measurement system is at first described then, starting from laws and directive applied in the European countries, the general characteristics and requirements of the transducers to be adopted are discussed and retrieved. Finally the measurement and control unit together with its sensing, hardware and software parts are presented.

Key words: Pollution Monitoring, Mobile Sensor Networks, Wireless Sensor Network, Data Fusion.

1. INTRODUCTION

The timely and reliable knowledge of pollution in urban areas has become, in recent years, one of the thorniest problems for local public authorities, even for the non-negligible impact in regard to political and social choices to be made. In particular many local authorities wish to offer continuous services about the determination of the pollution level, especially when they exceed limits that are considered unsafe or that are regulated by local laws [1].

In this scenario, the ability to have data timely, reliable and spread over the territory on which to base policies for the management of the urban community, can help to develop actions of safeguarding the health of the population, resource optimization and control of industrial and anthropogenic emissions, with the aim of improving the quality of life.

The typical set-up adopted to retrieve information on air quality is generally obtained through the use of fixed measurement units, positioned in suitable points of the area under test. These measurement units are characterized by good metrological performance somewhat counterbalanced by high costs, weights, dimensions, large measurement times, and power consumption requirements. Values of the pollutants in different areas are obtained by applying suitable mathematical models that calculate values in large areas. The position of these units must be appropriately designed to enable a reliable extension of the information collected throughout the range of interest. However, in cases where the hilly terrain or urban structure does not allow an extension of information to wide areas of territory, more monitoring stations have to be provided. Typically this leads to an increasing of the monitoring cost that sometimes become prohibitive for the interested authority.

If there is a need for accurate measurements in areas where fixed stations are not installed, some innovative solutions present today in literature suggest the use of mobile (i.e. *portable*) measurement systems that, in effect, re-propose the use of fixed units made transportable through the installation on trucks or carts [2]-[4]. Thus, measurement campaigns can be implemented in most parts of the territory, but the simultaneity of the data reported is closely related to the total number of systems used for surveying.

In this context, thus it becomes of interest to have mobile (i.e. *moving*) analysis systems which measures the quantity of environmental pollutions in most parts of the territory during defined paths of the vehicles on which they are installed.

In this way, the cost of urban pollution monitoring can be substantially reduced avoiding the use of many more expensive fixed or transportable monitoring units. Then adopting a suitable data management technique, it is possible to perform the integration of information in "clusters" of data; this makes possible, with a small number of devices, to achieve full coverage, accurate and timely provision of pollutions in wide areas.

Some measurement architectures have been presented in literature [5], [6].These solutions, however, does not fully consider the issue of the reliability of data collected from the standpoint of measurement uncertainty and of the maintenance of the metrological characteristics of the units during the whole operative cycle.

Thanks to their previous experience in the field of automatic measurement systems and sensing devices [7], wireless sensor networks [8] and uncertainty estimation [9] the authors propose a low cost mobile measurement system for the real time monitoring of environmental pollutions over urban areas. Key features of the proposed system, thought to be equipped on public urban ground transportation vehicles, are the significant low cost, the reduced dimensions of the measurement units, the autonomous power supply, and the measurement strategy able to minimize the measurement uncertainty. To this aim the measurement system implements suitable data fusion techniques that aggregate data acquired over the spatial and time domains.

In the following at first the general architecture of the proposed measurement system is presented; then starting from requirements of directives and laws operating in the European countries the minimum specifications for the

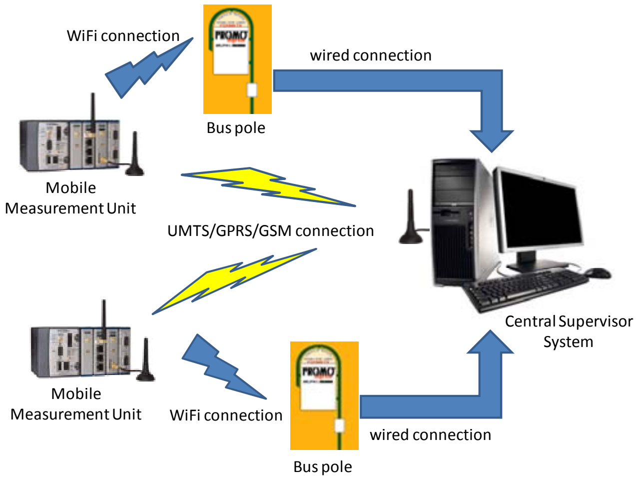

Fig. 1. General architecture of the measurement system

sensing devices are defined. Finally details about the measurement unit, the probe head, the considered sensors and the software architecture are given.

2. THE PROPOSED MEASUREMENT SYSTEM ARCHITECTURE

With reference to Fig. 1, the proposed system consists of:

- a series of Mobile Measurement Units (MMUs), designed to be hosted on board of vehicles, as urban service buses or service vehicles of the local authority.
- a Central Supervisor System (CSS).

The MMUs, which architecture and components are detailed described in section 4, are installed on the above mentioned public vehicles and perform the acquisition, the collection and the transmission of the measured environmental and of the geo-localization data. Measurement data are transmitted to the CSS by two alternative ways: a) by means of short-range WiFi™ connections installed at the bus poles; in this case the connection between the bus pole and the CCS is obtained by a wired LAN connection; b) by means of long-range UMTS/GPRS/GSM wireless connection.

The solution a) is a reliable and free of charge connection that guarantees high data rates but it is usable only at predetermined locations (bus pole); then it requires an off-line communication, usually sufficient to the pollution monitoring purposes. The solution b) performs an on-line communication on long-range distance (if there is an adequate network coverage), but it is generally characterized by a low data rate and not free of charge connection; then it is used only if the data must be on-line transmitted (e.g. alarms) or if the solution a) is out-of-order.

The CSS consists of a workstation equipped with the necessary devices for storing and viewing information and integrated with an UMTS/GPRS/GSM modem for on-line connection with the MMUs.

Using appropriate software specially developed, the CSS ensures:

- the management of involved MMUs by means of functions for enabling/disabling, control, configuring and verifying the MMU operation;
- the dynamic integration of data collected from different MMUs, with reference to mathematical models of pollution diffusion in the monitored area, and data fusion techniques to correlate data relating to the same location and detected by different MMUs;
- the representation of each MMU position and its measurement results on a digital cartography;
- the storage of the data collected in time series for their statistical analysis over time;
- the availability of the data processed on the Internet for a free use or a controlled use by the operators concerned.

3. THE ACTUAL EUROPEAN REGULATION AND MINIMUM TRANSDUCERS REQUIREMENTS

This chapter explains the legal regulations and limit values for the air pollutions parameters which has been considered for the selection of sensors and of the measurement system. It also shows the conversion rules used to pass from the law limits to resolutions and accuracies required. In Europe the presence of air pollutions is regulated by European Directive number 30 of the April 22-th 1999 related to environmental air quality limit values [10]. The considered quantities are the sulfur dioxide (SO_2), nitrogen dioxide (NO_2), nitrogen oxides (NO), particulate matter (PM) and lead, and in 2000/69/EC ambient air quality limit values for benzene (C_6H_6) and carbon monoxide (CO) are given [11]. In Italy it has been acknowledged by the Italian Ministerial decree number 60 of the 02/04/2002.

Typically norms and laws that consider the effect of pollution on the human body express the considered quantities as milligram on cubic meter (mg/m^3) or microgram on cubic meter (µg/m^3), while sensors accuracies and resolutions are expressed in parts per million (ppm) or parts per billion (ppb). To convert these units, the ideal gas law can be adopted.

Under normal conditions, the dry ambient air contains approximately 78.08% nitrogen (N_2), 20.94% oxygen (O_2), 0.93% argon (Ar), 0.04% of carbon dioxide (CO_2) and traces of other gases. Gas concentrations are usually expressed as a percentage volume. For an ideal gas, the percentage volume coincides with the molar percent.

Writing the ideal gas law as:

$$p \cdot V = n \cdot R \cdot T \tag{1}$$

where p is the absolute pressure (Pa), V is the volume (m^3), n is the number of moles (kmoles), R is the ideal gas constant equal to 8314.3 J/(kmoles K), and T is the temperature (K), it is possible to demonstrate that:

$$p \cdot V_e = n_e \cdot R_e \cdot T = \frac{m_e}{M_e} R \cdot T \tag{2}$$

with the e subscript indicating the considered polluting, m_e is the mass of the considered polluting, and M_e is molecular weight.

This implies that:

$$m_e = \frac{V_e \cdot p \cdot M_e}{R \cdot T} \tag{3}$$

Dividing both sides of (3) for the environmental volume (V_a) we obtain:

$$\frac{m_e}{V_a} = \frac{V_e}{V_a} \cdot \frac{P_0 \cdot M_e}{R \cdot T_0} \tag{4}$$

where P_0 is the reference pressure (101325 Pa) and T_0 is the reference temperature (273.16 K)

Equation (4) can be numerically written as:

$$\frac{m_e}{V_a} = \frac{V_e}{V_a} \cdot \frac{M_e}{22.41} \tag{5}$$

that relates the mass concentration expressed in kg/m^3 to the volume concentration expressed in ppm or ppb.

Considering the above national and international laws and decrees and the above-mentioned relations, it is possible to obtain the resolution and accuracy requirements for the considered transducers.

As for the carbon monoxide, the ministerial decree, the above-mentioned laws and decrees consider a maximum daily mean value equal to 10 mg/mc. Applying equation (5) and considering the standard pressure and temperature conditions, this means a mean daily value of 8 ppm. To this aim, a CO transducer with a resolution better than 0.5 ppm over a full scale greater than 50ppm can be considered quite adequate for the purpose.

As for nitrogen dioxides, the above-cited laws consider a hourly limit of 200 µg/mc and an annual limit of 30 µg/mc to protect humans and vegetations. The alert threshold is 400 µg/mc. Applying the above cited conversion rules, a value of 150 ppb is obtained. The choice of the NO_2 transducer must fall on a sensor that needs to work on a range from a minimum of a few tens of ppb up to several hundred ppb, also must be able to appreciate the variation of at least 10 ppb input resolution of about ten ppb.

As for the sulphur dioxide, the European directive considers a hourly limit of 350 µg/mc, a daily limit equal to 125 µg/mc and an annual limit of 20 µg/mc. The alarm threshold is 500µg/mc. This means a value of 122 ppb. A transducer able to quite satisfy the imposed requirements should work on a range from a minimum of a few tens of ppb up to several hundred ppb, also must be able to appreciate the variation of at least 10 ppb input resolution of about ten ppb.

The ozone is regulated with a hourly mean limit of 180 $\mu g/m^3$. This means a value of 84 ppb. A satisfying sensor should work on a range from a minimum of a few tens of ppb up to a maximum of a few hundred ppb, also must be able to appreciate the variation of at least 10 ppb input resolution of about ten ppb.

Finally, the benzene is regulated at a daily value of 5 µg/mc that is equal to 144 ppb. The choice of the transducer must fall on a sensor that needs to work on a range from a minimum of a few tens of ppb up to a maximum of a few hundred ppb, also must be able to appreciate the variation of at least 10 ppb input resolution of about ten ppb.

4. THE MOBILE MEASUREMENT UNIT

The core of the proposed system is the Mobile Measurement Unit (MMU). It is built according to a modular architecture, in which various sensors can be combined as required by the specific needs of the measurement purposes. The sensor assembly is also designed to be easily removed from the rest of the unit, in order to perform the check and periodic maintenance necessary to ensure proper traceability and accuracy of the measurements.

With reference to Fig. 2, the MMU is composed by four main sub-assemblies: (i) the probe head, (ii) the sensing, conditioning and acquiring devices, (iii) the processing and memory unit, and (iv) the data concentrator.

(i) As for the probe head, a schematic is reported in Fig. 3. It is composed by a package in which the sensing elements are suitably placed, and by a controlled air aspiration systems that is able to guarantee the desired air flux whatever is the vehicle velocity. In particular the sampling air port are placed in opposite direction respect to the vehicle direction, and the air flow is fixed by the aspiration system. In the probe head some fins able to impose a suitable air velocity for each considered sensing element are also placed.

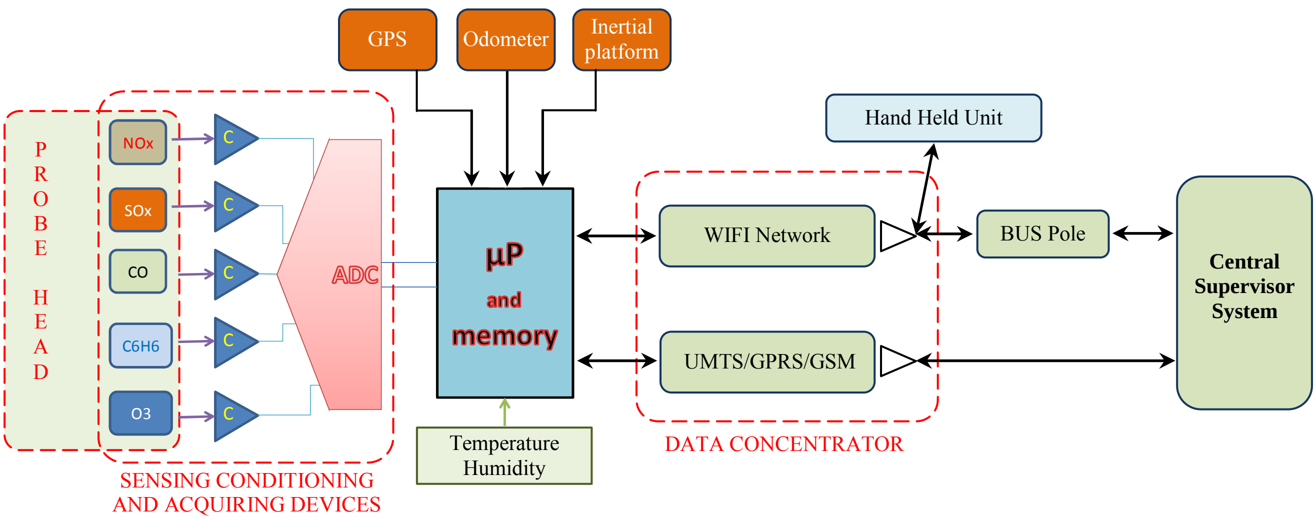

Fig. 2. Architecture of the proposed Mobile Measurement Unit

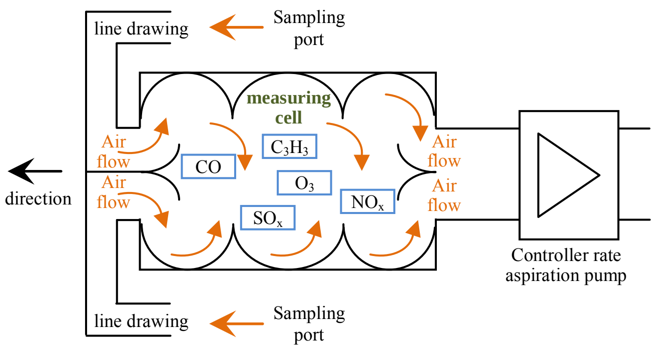

Fig. 3. Sketch of the realized probe head

(ii) At this stage, the sensing and conditioning circuit is developed to acquire the following quantities: air temperature; air humidity; vehicle velocity, and the concentration of Carbon monoxide (CO), Nitrogen dioxide (NO_2), Sulfur dioxide (SO_2), Ozone (O_3) and Benzene (C_6H_6). In the future version of the measurement unit also the fine particles (PM*X*) and other quantities of chemical interest will be considered.

The sensors are selected on the basis of both accuracy and measurement rate. At this stage, Kanomax™ Aeroqual sensors are used [12]. Table I shows the main characteristics of the selected sensors.

All sensors have an internal resistance that serves to bring the conversion head to a temperature that avoids any influence from external environment factors, such as atmospheric temperature and humidity, at the time of the readings. Moreover, they have the current output, typically closed on a resistance in the range 100-200 Ω, with the aim of falling in the voltage input range 0-5V of the analog to digital converter. Appropriate Kanomax ADC with 0-5V input range are available; in addition, these converters also have a RS232 output.

(iii) The processing and memory unit is composed by microprocessor and data storage hardware. The microprocessor manages the local unit and controls all the measurement and data acquisition tasks. The data are geo-referenced by means of a high-resolution GPS, together with an odometer and an inertial platform which are used to retrieve the geographic position even in areas not covered by GPS signal. The system also provides the local data storage necessary to save measured information between two successive data transmission to CSS.

(iv) As for the data concentrator, the unit has been equipped with some wireless mobile communication systems. In particular, a typical communication takes place by the WiFi TX/RX system and data are sent when the vehicle reaches the bus pole; if the WiFi-based data exchange is not possible, the unit is equipped also with a UMTS/GPRS/GSM data modem able to ensure the connection with the CSS. This second solution allow also a long-range communication to be provided.

Thanks to its modular architecture, the proposed system is structurally designed to meet the requirements of traceability, reliability and accuracy of measurements typical of such applications. In fact, each MMU is designed to permit the easy removal and replacement of each sensor. This allows the sensor to be properly calibrated and verified without the need to put the vehicle out of service. The removed sensor is then replaced by a previously calibrated sensor and is sent to laboratories certified for environmental measures that ensure its maintenance, testing and recalibration. In this way, the sensor is available for a new use avoiding periodic maintenance of the entire measurement system.

5. THE SOFTWARE ARCHITECTURE

The measurement and control software has been developed in LabView™ environment. The software is based on a client-server architecture and it is constituted by different modules running on different devices. In particular, two main software units can be identified: i) the program running on the MMU (which operates as "measurement server"), and ii) the program running on the external remote devices (hand-held units, laptop and so on, which act as clients).

As for the measurement server, once all the devices have been initially configured, the whole operating is completely automatic, with the user called to execute only the start and

Table I. Main characteristics of the selected sensors.

Measured Quantity	Calibrated Range [ppm]	Maximum Exposure [ppm]	Lower Detection Limit [ppm]	Accuracy	Resolution [ppm]	Response Time [s]	Operational Range	
							Temperature [F]	RH [%]
NO_2	0-0.2	0.5	0.001	+/- 0.01 ppm (0 to 0.1 ppm) +/- 10% (0.1 to 0.2 ppm)	0.01	<180	32 to 104	30 to 70
SO_2	0 to 10	20	0.2	+/- 0.5 ppm	0.01	<60	-4 to 104	5 to 95%
CO	0 to 100	200	0.5	+/- 5ppm	0.1	<150	32 to 104	5 to 95
O_3	0 to 0.5	1	0.001	+/- 0.008 ppm (0 to 0.1 ppm) +/- 10% (0.1 to 0.5 ppm)	0.001	<60	23 to 104	5 to 95
C_6H_6	10 to 1000	n/a	10	10 ppm	0.1	<20	23 to 104	5 to 95

stop actions. All functions (data acquisition from sensors and external devices, processing and transmission) have been implemented into the firmware of the embedded PC. More in detail, the firmware processes the data acquired from transducers and from the devices devoted to the geo-localization (GPS, odometer and inertial platform). These data are stored on the internal hard disk (as suitable files). In addition, the firmware manages the connection and the communication with the external devices.

As for the clients, the developed software (control software) requires a connection with the server to retrieve and display data collected by the MMU as well as to provide some control commands able to change the MMU operating.

As an example, in a standard working session, the acquiring procedure (running on the MMU) goes in a standby phase until a start commands is given. The control software (running on the client), after the MMU is identified on the network, establishes a connection with MMU with the aim of controlling their status and measurement settings as well as manage the stored files. At the same time, the download software (running on suitable unit placed on bus poles) continuously scans the network to connect with the MMU, and then downloads all data previously stored in the MMU internal hard disk.

6. CONCLUSION

The paper proposes an effective architecture for mobile systems involved in urban pollution monitoring. It is constituted by two main classes of devices: a mobile measurement unit (MMU) and remote nodes which in turn can be used either for control the MMU (and then the measurement settings) and download data collected by the MMU. The mobile measurement unit is made to be installed on public vehicles and is able to perform pollution monitoring during the usual vehicle service. The modular architecture assures good feasibility and efficiency together with a simplified maintenance procedure. The proposed measurement system is thought to provide the collected data to a suitable central supervision system which controls many measurement units and use the acquired data to perform a spatial pollution evaluation in the area of interest (as an example by means of suitable data fusion techniques).

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