PERVASIVE SENSOR NETWORK FOR REAL TIME ENVIRONMENTAL MONITORING IN CONSTRUCTION SITES

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ABSTRACT

In order to gain competitiveness and compete at a global level, construction companies should improve their efficiency. The problem is even more relevant in the construction field, whose work processes find it hard to evolve towards new automated methods and techniques in the management field. For that reason, this paper suggests how construction companies could apply new technologies to implement automated management of environmental hazards.

Based on a survey regarding the environmental risks presently experienced in construction sites, noise and dust were considered two of the main hazards. So in this paper a networked system for real time remote monitoring of the spatial distribution of dust in construction sites was developed. Such a system would relieve builders from the commitment of on-site surveys, allowing for a continuous monitoring of the site conditions and of the real exposure of each worker and pass-by to the pollutants generated by construction works. The main system requirements considered are: easy to deploy, reliable, as accurate as needed to be able to send real-time warnings and store a good estimation of the real exposure to which involved people have been subject to.

So far the research produced a prototypical hardware for dust monitoring made up of wireless sensors which can be easily deployed on site. The sensors were calibrated by means of laboratory tests, where their measurements were compared with those collected by means of highly accurate instruments, which were taken as a reference. Thanks to these experiments, calibration curves for the sensors were worked out, showing also the measurement range of the sensors.

KEYWORDS

Automation and Robotics, remote sensing, construction sites, environmental monitoring.

INTRODUCTION

Presently, construction companies are facing the challenges risen by the global economy scheme. In fact, they are trying to increase their productivity and to provide high quality products and the safest working conditions ever to their workers. Hence, much research is focused on the aspects of cost-effective construction management, intelligent waste handling and improvement of safety at work (A. Giretti et al., 2012). First, setting up a cost-effective construction project management would include material management and inventory traceability which conceivably contribute to the construction process (Weisheng et al., 2011). Automated progress monitoring would reduce the burden of work usually required to produce editing of project reports (Navon and Goldschmidt, 2003). Communication can be made easier through automated visualization of construction data and information awareness is an undisputable excellent tool to manage machines (Chao-Ying and Russel, 2011). Secondly, automated waste management is aimed at improving its effectiveness, in terms of reduction of non-recycled fraction and cutting environmental impacts down (Shen et al., 2004). Hence, several studies suggested specific methods and procedures to reduce the generated waste at its origin (Poon et al., 2004). In general, providing a safe working environment to employees may translate into different practical situations, such as automated control of proper wearing of safety gears, signaling hazards in real-time, automated predictive collision detection and fall hazards warning in crowded site’s areas, and so on depending on the particular kind of work to be performed. The focus of this paper relies on automated management of environmental hazards.

The first aspect of this issue is relative to the assessment of the environmental impacts caused by construction execution (Chen et al., 2004); similarly, carbon emission simulation tools for construction project are under development, which are thought to be of great help in highlighting the most harmful sub-phases over the overall process (Wong et al., 2012).

The second relevant aspect concerns worker exposure to harmful environmental pollutants, e.g. dust, noise, gases. Findings from on-site surveys showed silica exposures above admissible thresholds are almost always experienced by workers involved in common construction tasks (e.g. abrasive blasters, jackhammers, rick drills etc…) and their personal protection equipment is often inadequate for the exposure encountered (Flanagan et al., 2007). Currently, monitoring is performed either by stationary measurements or by personal monitoring, i.e. equipping some of the workers present on site (Croteau et al., 2004).

For that reason, this paper will contribute to a system for automated monitoring of dust concentration in construction sites: in fact, such a system would allow to perform a spread and accurate monitoring all over the whole site area, overcoming the traditional approach based just on spatial and temporal samplings. The proposed system was shown to be able to automatically collect data about the dust concentration caused by construction works.

DUST MONITORING IN WORKPLACES

Admissible dust concentration thresholds are ruled by governments all over the world. This is due to the serious health hazards that can be caused by fine dust, contributing to or even causing respiratory and cardiovascular diseases. Although several permissible values have been set by the ruling and advising organizations, one of the most distinguished references in the field is the recommendations given by the World Health Organization (WHO), which refer to the annual and daily average exposures to pollutants (WHO, 2005). The WHO recommendations are organized into the two different classes: PM2.5 and PM10. More importantly, the WHO clearly assessed the importance of long-term exposure monitoring to pollution, besides short-term. More insights into the threshold limit values (TLV) in occupational matters are provided by the publications edited by the American Conference of Governmental Industrial Hygienists (ACGHI, 2012).

PM exposure in construction sites is strongly dependent on the kind of activities. The main harming component is silica, which is found in most of them (Flanagan, 2003). However monitoring has been resulting as a cumbersome activity, because it involved – in the best case – the use of wearable instruments, which are hardly accepted by workers. Current standard measurement equipment is large, expensive and sparsely deployed (Budde et al., 2012), because mostly based on the use of gravimetric measurements and laboratory analyses. As a result, we need fine-grained, mobile and distributed measurements, e.g. to identify hot-spots or monitor people at risk. PM monitoring is also common in other crowded environments, such as metro stations. A survey carried out in the Barcelona metro used a high volume sampler (30 m^3/h) programmed to sample PM10 and PM2.5, an optical counter and a laser-scanner optical counter (Querol et al., 2012). Not only were these instruments shown of being quite invasive, but the collected data required to be post-processed by qualified laboratories.

The new monitoring system targeted to construction sites

This paper suggests to set up a real-time monitoring system which is capable of crosschecking the position of workers and the estimated dust concentrations over the site. Such a system would provide at least a couple of significant services in construction sites:

- capability of signaling in real-time the overcoming of any predetermined threshold values;
- gradual implementation of a database containing the cumulative value of the amount of PM concentration to which workers have been exposed, integrated over several possible meaningful time windows.

In the schematic shown in Figure 1 every worker is supposed to be tracked using one of the available position tracking systems thought for construction sites; then the new sensors described in this paper are deployed over the site and programmed so as to give back in real time the dust concentration values at their known positions (in order to work like that, even they need to be equipped with a wireless tag device for being automatically located).

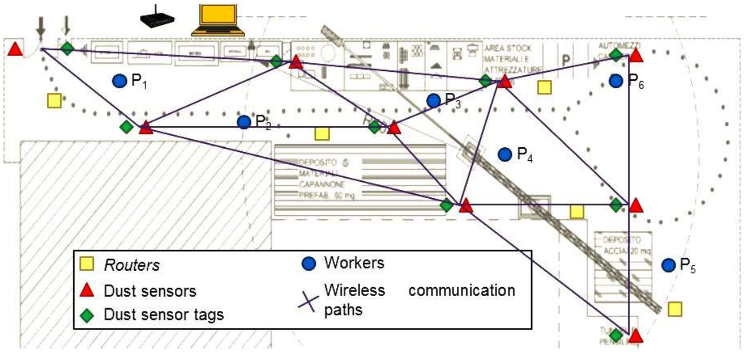


Figure 1 – Schematic of the monitoring system logics.

In the first step of this research, a preliminary network prototype to monitor the concentration of particulate matter - PM10 - was developed and tested in the machine laboratory of the DICEA Department and of the SIMAU Department at Università Politecnica delle Marche (Ancona, Italy).

DEVELOPMENT OF THE LOW-INVASIVE SENSOR NETWORK

The dust sensors

The dust sensors, as labeled in Figure 1's legend, must be able to perform a real-time monitoring of dust levels in air. There are not so many commercial off-the-shelf probes available, which comply with the requirements of: low-power, small enough to be incorporated into hand-held devices, good accuracy. Our market search gave back two main manufacturers: Shinyei and Sharp. Both products are based on the same operation principle: a light beam is emitted into a measurement chamber; when dust is present, the light is refracted by particles and the amount of scattered light is detected. One unique feature of the first set of sensors is that Shinyei ones use a heating resistor to create an updraft. On the other hand, the Sharp GP2Y1010 optical dust sensor is mostly used in air quality equipment, such as air purifiers.

After our first assessment for the applications outlined above, some of the drawbacks in the use of the heating turned out to be increased power consumption and longer response time, since it takes some time until the resistor is heated up. So we selected two Sharp GP2Y1010 optical dust sensor (112 and 113 in the following), since they are cheap, small, low-power (Table 1).

Table 1 – Main parameters of the Sharp GP2Y101AU0F dust sensor

Parameter	Units	Typical Value	Constraints
Supply Voltage	V	-0.3 to +7	Ta = 25°C
Operating temperature	°C	-10 to +65	
Sensitivity	$V/(0.1mg/m^3)$	0.5	Ta = 25°C; Vcc = 5V
Output Voltage at no dust	V	0.9	Ta = 25°C; Vcc = 5V
Consumption current	mA	11	Ta = 25°C; Vcc = 5V

Technically, the Sharp dust sensor's measurement chamber causes a pulse whose voltage is proportional to the number of particles which caused the light beam to be diffracted (Vs,i). The microprocessor works out the mean (V_s) based on the last 16 records. V_s is then turned by an Analog to Digital Converter (ADC) into an integer number (L) with 10 bit resolution (R=10) and interfaced to a PIC 24F32KA302 microprocessor (Figure 2). The ADC uses a 1.8 V reference voltage (Vref). A voltage divider is installed before the ADC to avoid its saturation for V_s grather than the reference voltage V_{ref}.

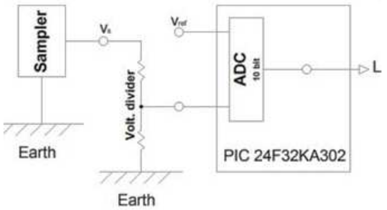


Figure 2 – Electronic schema of the dust sensors 112 and 113.

Description of the monitoring network

While it is expected that the accuracy using simple devices is lower than that of expensive stationary equipment, mobile measurements would allow for a much higher spatial and temporal resolution. Also, unprecedented services would be straightforwardly available: mobile dust sensors could be applied in construction sites to record the workers' occupational exposure to dust; workers might want to be sure on an informal level that they are not overexposed to high concentrations of particulate matter in the long-term.

The wireless communication system used to form the pervasive network is very similar to that one described in more detail within (Naticchia et al., 2013) and which is the property of the Italian company Smart Space Solutions srl. It was made up of detached devices, with no cabling neither for communication nor for powering, hence battery-powered. It exploits hardware and software components based on the IEEE 802.15.4 standard medium access and Zig-Bee stack communication protocol. A ZigBee-based communication network comprises three kinds of devices: one or more coordinators are used to initiate network formation, acting as 802.15.4 PAN (Personal Area Network) Coordinator (that is a full-function device, like in Figure 3-a) and as a Gateway to the local PC or web connection; fixed devices with routing capabilities (Routers) are installed at known locations (only if localization is required, but the known position is not needed for pure communication purposes) of the area being monitored, and are in charge of performing multi-hop routing of messages, following a pre-assigned balanced tree routing scheme, which can be modified at runtime (Figure 3-b).


(a) (b) (c) (d)

Figure 3 – PAN coordinator/gateway (a) of the network, routers (b), dust sensors 112 and 113 (c), and one of the end devices uncovered to show the integration of the (red circled) Sharp dust sensor (d).

Finally, end devices (or tags that are reduced function devices - RFD) are used as mobile nodes. So dust sensors (in the following labelled no. 112 and 113) have been embedded inside RFDs, in order to be potentially put on mobile facilities, given the ability of RFDs to be tracked (Figure 3-c). The low power features of the network are guaranteed thanks to a reduced router duty cycle operating in the asynchronous mode. The dust sensor was driven according to the schema in Figure 2. As shown in Figure 3-d, integration of the dust sensor in the RFD device also required to practice a hole where air is allowed to flow through and the light scattering measurement can take place.

LABORATORY EXPERIMENTAL CAMPAIGN

Proper calibration of the light scattering measurement to an estimate of particle concentration requires the development of customized conversion equations. Hence, such dust sensor was calibrated against a co-located filter-based technique instrument in the same area, which allowed to work out a proper conversion factor from scattering to a particular mass per unit volume ($\mu g/m^3$) estimate (Padgett et al., 2008). Prior to this, the range of the sensors was investigated by means of its exposure to high concentration dust: two dust sensors were placed inside an enclosure 0.83 m^3 big, where dust was generated by means of brick grinding (please refer to Figure 4-a). The dust concentration plots are shown in Figure 4-b: the three plateau, which were had when the plot of sensor no. 112 reached its maximum, represent the maximum digital value readable by this kind of sensor (L_{max}= 850), while minim values are close to zero, in this particular case L_{min} = 15.

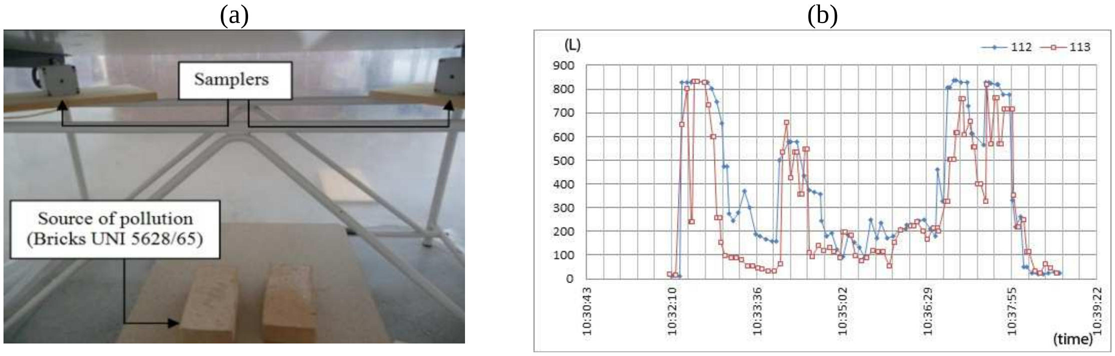
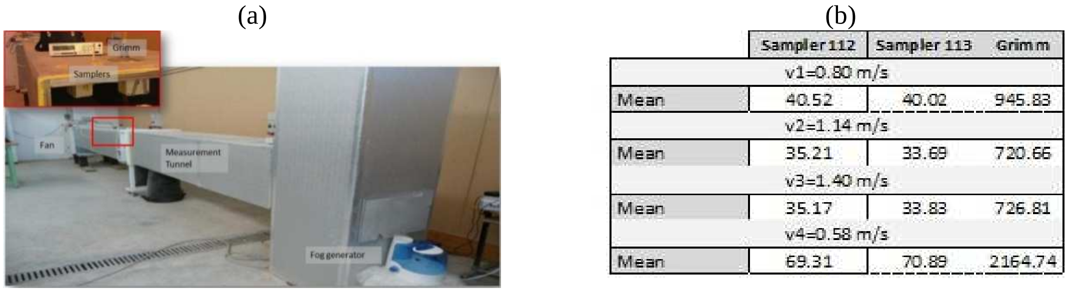

(a)
(b)

Figure 4 – The enclosure used to estimate the range of the dust sensors (a) and the plots generated by the roofs (b).

Calibration was finally performed using the experimental setup in the SIMAU laboratory (Università Politecnica delle Marche) in Figure 5-a: one fan was positioned at the end of a measurement duct, which was able to conserve isokinetic conditions during each sampling. An optical particle counter Grimm 1.108 was used as a benchmark (depicted in the top left red squared box in Figure 5-a). This portable laser photometer with a constant volume flow of 0.6 l/min and a digital display also embeds a removable 47mm PTFE filter for collecting all the measured dust, so that after the end of the trial an appropriate density verification/correction is possible. This filter is also the base for legal mass monitoring. Field mass calibration to local dust conditions can then be achieved by simply removing and weighting the filter, giving a chance to make specific density corrections for the measured instrument mean dust mass of the monitored area. Dust generation was provided through an ultrasonic fog generator placed at the inlet of the measurement tunnel (0.7x0.7 m squared cross section). The ultrasonic fog generator uses ultrasonic technology to vaporize a salt solution to produce a fog composed of 10 micron and less sized water particles which gives smaller solid micron particle diameter (Fava et al., 2012).

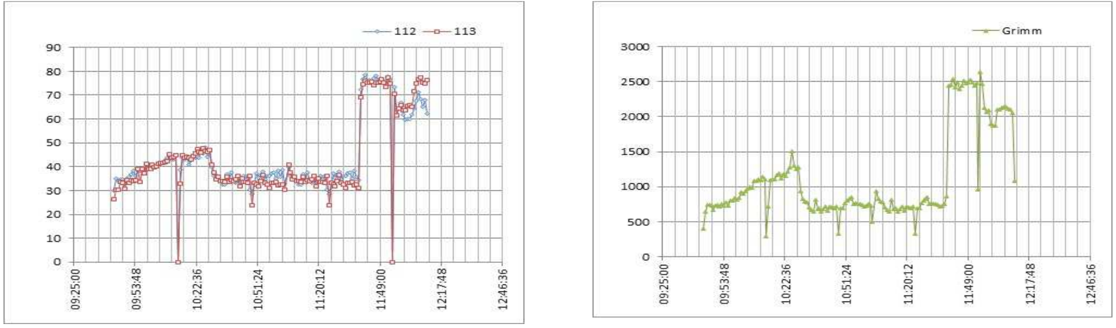
Results from the trial are shown in part b) of Figure 5 and in Figure 6. In particular Figure 6 compares side by side the readings from dust samplers and the number of particles counted by the Grimm reference instrument. The whole trial was split into four segment, each characterized by a different value of air speed in the measurement tunnel: starting from 0.80 m/s it was increased until 1.14 m/s and 1.40 m/s, falling down 0.58 m/s in the last part.


(a)
(b)

	Sampler 112	Sampler 113	Grimm
	v1=0.80 m/s		
Mean	40.52	40.02	945.83
	v2=1.14 m/s		
Mean	35.21	33.69	720.66
	v3=1.40 m/s		
Mean	35.17	33.83	726.81
	v4=0.58 m/s		
Mean	69.31	70.89	2164.74

Figure 5 – Experimental setup for calibration of sensors 112 and 113 (a) and results got from measurements (b).

From Figure 6 it is clear that the dust samplers are coherent with the benchmark, being both trends of the same type. When the speed is varied the plots leap accordingly (the plot leaps up in case air speed is deceased while it leaps down when air speed is increased). Figure 5-b compares in a row the three mean values estimated by the two samplers and the Grimm during the four time spans when air speed were kept constant. Based on those data, conversion factors were estimated as a final step.


(a)

(b)

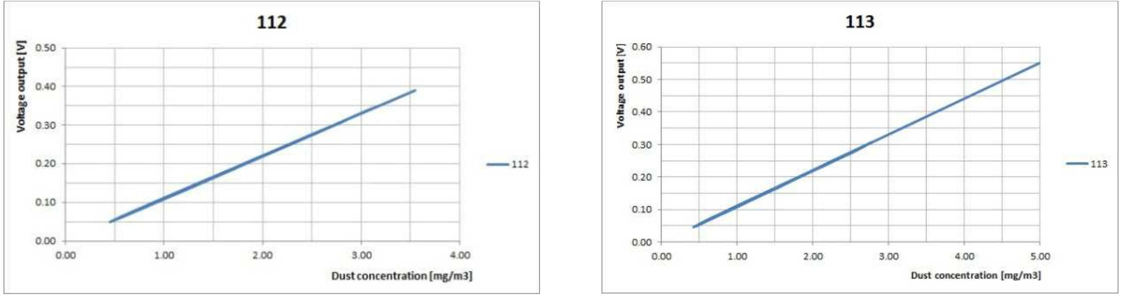
Figure 6 – Samplers (a) and Grimm (b) measurements collected during the experiments.

Starting from the trial duration, also thanks to the knowledge of the volume flow suctioned by the Grimm and the weighed dust filtered by the instrument in the same period, the average dust concentration in air over the trial was computed, like in the two left columns in Table 2. The right part of Table 2 lists the average number of particles measured by the instruments and conversion factors that relate each number to the average concentration already mentioned. Those values might be used to convert the readings from the samplers into concentration values. As the last step, two calibration curves were worked out to relate the concentration values to dust concentration. The conversion factors were used to relate every reading in Figure 5-b to the corresponding dust concentration, and the calibration curves in Figure 7 were given: both sensors have an x-offset around 0.5 mg/m^3, while their sensitivity is 0.11 V/(0.1mg/m^3).

Table 2 – Computation of conversion factors

Gravimetric measures	
Trial time span [min]	184
Grimm air flow [l/min]	0.60
Total volume flow [l]	110.40
Total air volume [m^3]	0.11
Weighed dust mass [µg]	140.76
Weighed dust concentr. [µg/m^3]	1279

Particle counters		
GRIMM	Mean number of particles	116.68
	Grimm conversion factor	**1.14**
Samp. 112	Mean digital value	40.68
	Conversion factor	**31.34**
Samp. 113	Mean digital value	39.68
	Conversion factor	**32.13**


(a)

(b)

Figure 7 – Calibration curves for sampler no. 112 (a) and sampler no. 113 (b).

CONCLUSIONS

The work reported in this paper was targeted to setup a network for real-time monitoring of particulate matter (PM10) in construction sites. Both the low-invasive communication network and the good reliability of the end-devices – in charge of estimating the real dust concentration – showed the feasibility of the whole system. The setup is now ready for applications in construction, whose design must take into account that the lowest threshold that can be monitored by the system is about 0.5 mg/m3. Hence the system turned out to be suitable for monitoring areas at risk and pollution hot spots, while it is not suitable to evaluate air quality, because not capable of falling under the aforementioned threshold, which is above the air quality value recommended by WHO.

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