A Low-Cost Solution for the Monitoring of Air Pollution Parameters Through Bicycles

A low-cost solution for the monitoring of air pollution parameters through bicycles

Irene Aicardi[1] (0000-0002-7986-0235), Filippo Gandino[2] (0000-0001-5581-1159), Nives Grasso[1] (0000-0002-9548-6765), Andrea Maria Lingua[1] (0000-0002-5930-2711), Francesca Noardo[1] (0000-0003-2269-5336)

[1]DIATI - Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, c.so Duca degli Abruzzi, 24 10129 Torino Italy
(irene.aicardi, nives.grasso, francesca.noardo)@polito.it
[2]DAUIN - Department of Control and Computer Engineering, Politecnico di Torino, c.so Duca degli Abruzzi, 24 10129 Torino Italy
filippo.gandino@polito.it

Abstract. The monitoring of air quality parameters is a fundamental requirement for smart cities development and it is of primary importance for the quality of human life. In fact, the knowledge of air quality parameters along the days and in different areas of the city is essential to monitor its behavior and to take some preventive measurements to limit the concentration. Especially in big cities, it is very hard to have widespread updated data about pollutants and air quality parameters since normally only few air quality monitoring stations are available. In Piedmont (Italy), the reference public body for this kind of information is the ARPA (Regional Agency for the Protection of the Environment) which is responsible for the collection and the disclosure of environmental data. However, the number of monitoring stations along the city is limited and they have fixed positions. A solution through mobile sensors would be preferable to have a more comprehensive description of the phenomenon. In this paper, the authors describe the implementation of a new solution based on a mobile system to house environmental air quality and imaging sensors (since also the knowledge of the shape of the environment is a fundamental aspect). In particular, a bicycle is adopted and the paper describes all the analyses involved in the choice of the more appropriate sensors and their evaluation and behavior in a real environment. Finally, the collection and management of the acquired data is analyzed through the implementation of a dedicated GIS (Geographical Information System).

Keywords: environmental monitoring, low-cost sensors, pollution, semantic data management, dynamic scenes

1 Introduction

Air quality in urban scenarios is considered one of the greatest threat to human health since it is fundamental to support the human life [3, 6, 11, 15, 19]. Especially, in a densely populated urban environment it is very difficult to manage this kind of aspects since everyday activities contribute to increase the degree of pollution of the cities. The number of cars is significantly increasing and the streets are also full of busses and motorbikes that are source of air pollution in terms of fossil fuel combustion. Moreover, also the heating systems of the buildings are a relevant source of pollutants in urban areas.

In this scenario, the knowledge of the pollution distribution along the days and the areas can be an important source of information that people can use to make their own choice about the use of transports and their daily life [9]. To date, most of the information in Piedmont are acquired by fixed stations (usually located by the ARPA). These data are really accurate, but the use of fixed stations means to do not have the capability to perform dynamic analyses and have widespread information to observe the distribution of pollution along the whole urban area. In fact, a pervasive knowledge of the air quality can help to understand how it changes during the day and how it is spread. This kind of knowledge can derive from spatially and temporally accurate and well distributed data about the air quality.

This information is one of the fundamental points for smart cities development. In fact, a lot of big cities are introducing the monitoring of multiple parameters along the urban areas through the use of wireless sensors networks (WSNs). This kind of technology uses low-cost sensors devices well spread along the area of interest that can collect data at the same time and send them to control stations that have the ability to perform the analyses. These technologies are then used to improve the services offered by the city and to increase the quality of the people life. An example of the use of this approach is reported in [16] where a WiFi-based system is adopted to collect the acquired data and transmit them to a neural network that have the ability to perform the processing, extract the information and public the results to a dedicated web page. Also [10] tried to use WSNs systems to monitor the air pollution in Mauritius through the use of static sensors. The technology is described in details and also the use of the network is deeply investigated through different kind of simulations.

However, many static sensors would be required in order to provide a dense coverage. For this reason, different mobile systems have been investigated along the years by the scientific community. In order to have widespread data, different studies began to incorporate low-cost sensors across the cities. For example, [12] proposed a monitoring system made by fixed and mobile sensors also mounted on public vehicles, such as buses, taxis and other public transport. Also in this case, data were collected through a wireless transmission and managed through a data mining technique whose analyses were made through simulations. Moreover, also [8] tested the possibility to use public transports to house mobile sensors and to have a more sophisticated spatio-temporal resolution of the data. The use of bicycles was already investigated by [5] to monitor pollution parameters through dynamic sensors easily installable on them. The main idea is to have a system that people can easily use by their own in a participatory framework. Following this idea, [4] proposed a dynamic monitoring system based on handheld devices that people can use to measure pollutants in the air and whose data constitute a network to monitor specific areas. In this regards, also [7] proposed a participatory system where the devices were directly connected to the smartphones of the people. This approach allowed to have very widespread data, but with the difficulty to individuate problems related to the accuracy on the use of these low-cost sensors integrated in low-cost smartphones.

Another fundamental information that is correlated to pollution is the three-dimensional shape of the analyzed environment. For this reason, the simultaneous creation of a 3D model can be the best approach to cover this lack of information. 3D models of the buildings are often realized starting from laser scanner techniques which, however, are expensive both in terms of time and costs. For this reason, in recent years, photogrammetric techniques based on images have been investigated and taken to 3D models generation. The advantage of these techniques is the acquisition speed of the data and the low cost of the used instrumentation (photographic cameras). Moreover, the advantage of these systems is their ability to be mounted on mobile systems allowing rapid and dynamics acquisitions. The models thus created can be used as bases in the 3D mapping database.

In this scenario, the idea is to develop a low-cost system for the continuous, dense and frequent monitoring of the air quality. The proposed system would be integrated on low-impact vehicles (such as bicycles), it would be used to get information useful for urban planning and the data would be real-time available on the Web and accessible by users. The proposed system is a part of the 'Cyclair' proposal included in the Torino Living Lab project[1] with the aim to promote the use of the bicycles as a means of urban transport and to raise awareness about the link between air pollution and transportation also through the direct involvement of users. A student team (Policycle) financed by the Politecnico di Torino was involved in the implementation of the system and in its application.

The project is subdivided into two levels of details:

- the development of an acquisition system installable on low-cost and low-impact vehicles: it allows to acquire all the necessary data to collect air pollution and environmental parameters. It is constituted by:
  - navigation sensors for the positioning and attitude estimation of the system;
  - imaging sensors (such as digital cameras or panoramic cameras) for the acquisition of visible information useful to describe the context;
  - environmental sensors for the collection of air pollution and quality data;
  - data storage systems and real time wireless communication platform to broadcast the acquired data;
- a dynamic spatial database for the management of air quality data: it is based on the Open Geospatial Consortium (OGC) CityGML standard data model, extended to handle dynamic environmental parameters. The developed platform is able to:
  - realize post-processing operation to integrate the acquired environmental data;
  - store the data on a GIS platform;
  - perform real time analyses and visualizations;
  - carry out analysis to estimate qualitative air quality indicators.

The paper describes the developed systems, the used sensors and the methodologies to verify their data, and the implementation of a spatial database for the data management. The system is finally applied to a real case study in Torino where imaging and air pollution data were collected.

---

[1] http://torinolivinglab.it/

2 Implemented dynamic system

The main benefits of a mobile monitoring system are to increase the spatial density of the collected measures. Therefore, with respect to a static system, it is possible to use less sensors by covering the same area. Private or public vehicles (daily used by citizens) can be evaluated as monitoring systems, and our attention was more focused on public and sharing vehicles (in particular bicycles). The advantages in the use of bicycles are mainly two: they do not produce pollutants and they are very flexible monitoring systems since they are able, for example, to access areas not open to cars or busses. Moreover, the system for the air quality monitoring should be able to: monitor a large area, collect pervasive data, guarantee a proper level of accuracy, involve limited costs. For these reasons, the acquisition system for air quality monitoring data has been mounted on a bicycle and it is equipped with:

- navigation sensors for the definition of position (GNSS) and attitude (IMU);
- environmental sensors (temperature, humidity, pressure, PM10, PM2.5, PM1 and ozone).
- imaging sensors (digital cameras, webcams and panoramic 360° cameras);

Regards to the navigation sensors, two different systems were adopted:

- a Microstrain 3DM-GX3® - 35 (Fig. 1 left);
- a Ublox EVK-M8T (Fig. 1 right).

The Microstrain system allows to independently acquire accelerometers, gyroscopes and magnetometers data that can be synchronized thanks to an internal GNSS receiver (u-blox system). This allows to have a positioning solution with a metrical level of accuracy (since no Kalman filter is applied) [14]. This device was selected for its weight and size (summarized in Table 1), very interesting for bicycles.

Table 1. Main features of Microstrain 3DM-GX3 – 35 [14].

	Accelerometer	**Gyro**
Measurement range	±5 g (standard)	300°/s (standard)
Non-linearity	± 0.1 % fs	± 0.03 % fs
Bias instability	± 0.04mg	18°/ h
Initial bias error	± 0.002 g	± 0.25°/s
Noise density	80 µg / √Hz	0.03° / s / √Hz
Sampling rate	30kHz	30kHz

The Ublox EVK-M8T device was used to have positioning information of the acquired images. In fact, it was directly connected to the webcam and acquired synchronized data. It is connected to an active antenna able to acquire GPS/GLONASS/BeiDou data and it is really easy to use and user-friendly, so that it can be easily managed also by no expert users.

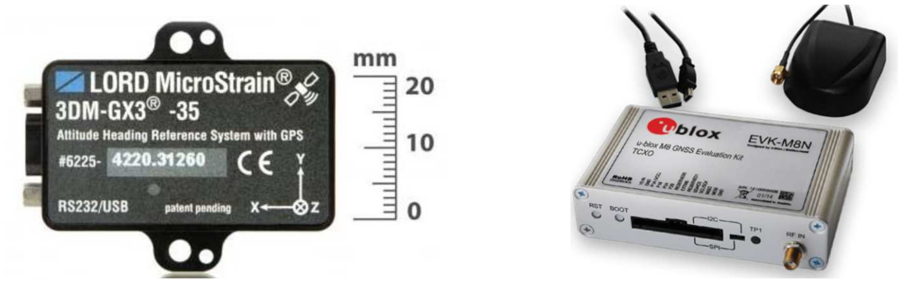

Fig. 1. Microstrain 3DM-GX3 - 35 (on the left) and Ublox EVK-M8T (on the right).

For the pollution data, it is fundamental to define a system with the capability to be cheap, easy to use and able to produce reliable data to effectively develop a low-cost monitoring system. Looking at the systems available on the market and in the research field, the Waspmote Plug & Sense from Libelium has been selected [21]. In fact, it has been adopted also for other international research projects. For example, in Pisa (Italy) as monitoring system [1] and in industrial and urban areas [13] as air quality monitoring system. Its main evaluated characteristics are:

- compliance with ground level dust and ozone sensors;
- compliance with complementary sensors, such as ammoniac, nitrogen dioxide, atmospheric parameters and noise;
- possibility to integrate wireless communication systems (e.g., Zigbee, WiFi);
- easy programmability through the C++ language for Arduino;
- international protection level IP65, compliant with outdoor deployment;
- low cost, required for a pervasive network composed by many sensors.

The mobile stations were equipped with sensors for the acquisition of data related to ozone, pm10, pm2.5, pm1, temperature, humidity and pressure. Each station is able to work autonomously, acquiring new data every 30 seconds.

Finally, in order to assess the possibility of creating a photogrammetric 3D model of the urban environment starting from spherical images, they were acquired with the spherical camera NCTech iSTAR (Fig. 2 rectangle 5).
Georeferenced images acquired by this sensor can be used to assess the state of the roads or the bike path or, in addition to the spherical images, for the 3D generation of the environment.

Each sensor has its own system to collect and store the data. Webcams were directly connected to a computer for the acquisition start and stop and for the data collection options, also the panoramic camera has its dedicated computer, while the Waspmode autonomously collects data that can be downloaded through a WiFi connection.

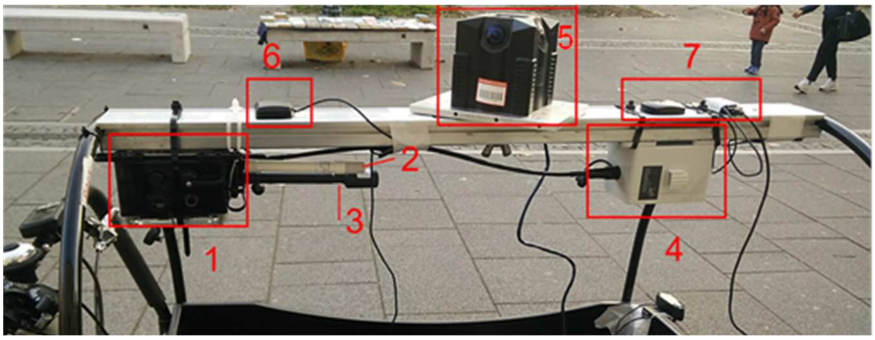

Fig. 2. Acquisition system mounted on the bicycle: 1. Wapmode Plug & Sense; 2. temperature, humidity and pressure sensors; 3. Ozone detection sensor; 4. fine particles detection sensor; 5. NCTech iSTAR.; 6. Ublox antenna; 7. Microstrain 3DM-GX3 - 35 and its antenna.

3 Sensors evaluation: experimental analysis

3.1 Air quality monitoring system

The main goal of the air quality monitoring system is to provide a qualitative information of the dust and ozone concentrations with a high spatial and temporal data density. However, the implementation of a distributed network of sensors does not allow to use expansive sensors. Therefore, a mobile distributed system can provide a larger quantity of information with respect to fix stations, but with a lower accuracy. In order to evaluate the reliability of the achieved data [20] some tests have been executed on the sensors and Fig. 3 shows the results of two OPC-N2 particle sensors.

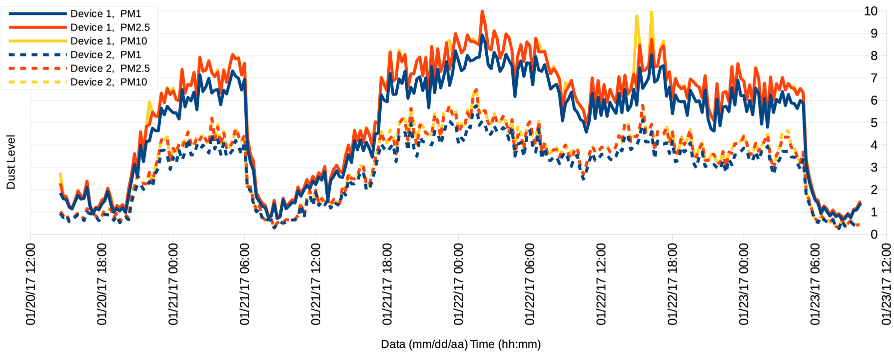

Fig. 3. Dust levels captured by two devices.

The solid lines show the PM1, PM2.5 and PM10 collected by the first sensor, while the dashed lines show the values collected by the second device. The experiment was performed over 3 days in a room with a forced air system able to filter the dust. Both the sensors performed a measure for 15 minutes. Every datum is related to the dust analyzed during 5 seconds. Each sensor collected 270 measures. It is possible to ob-

serve that the dust filter was active between the morning and the evening of February 20, 21 and 23, while it was inactive during the nights and on February 22. Both the sensors were able to sense all the transitions.
In order to obtain a better comparison, a normalization was executed on the first 135 records, that was used for training. For each sensor was calculated the average and the variance of the training records, then the average was subtracted and the resulting data were divided by the deviation. Fig. 4 shows the normalized data. It is possible to observe that for all the lines the average over the first 135 records is zero and the variance is one. The normalized data are very similar, as shown in the chart. The last 135 records were used for test. The average and the deviation computed on the training data were used to modify also the last part of the chart. It is easy to observe that the average of the last 135 records is over zero. Although the normalization was based on other data, it provided good results even on the records used for test. The results of this test show that it is possible use mathematical formulas to compare the data.

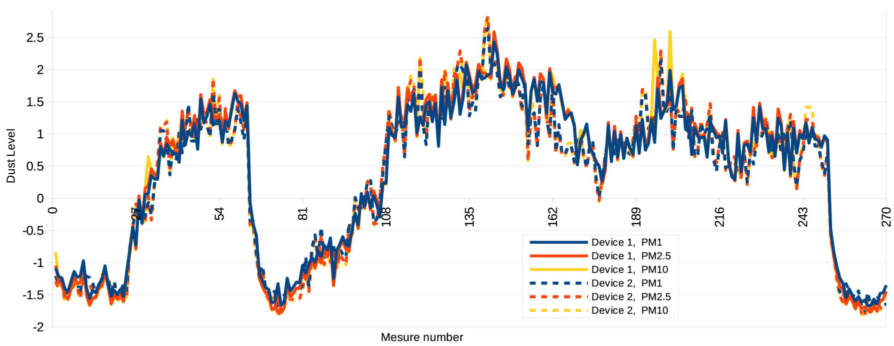

Fig. 4. Normalized dust levels.

Finally, the collected data were sorted according to the intensity of the particulate measured by the first device. Fig. 5 shows the sorted data. Although the data collected by the second device are not steady, they clearly identify the increasing trend.

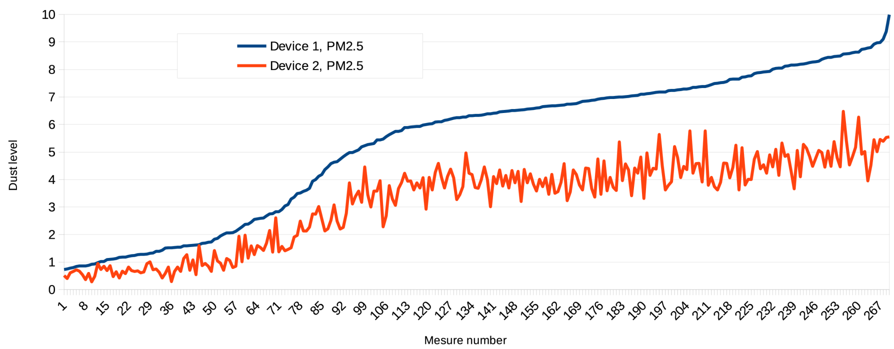

Fig. 5. PM2.5 data sorted by intensity level captured by device 1.

3.2 Imaging sensors calibration

To generate the 3D model of the environment through images, a panoramic camera NCTech iStar was adopted that is able to simultaneously acquire 4 images that can be subsequently stitched to generate a spherical image.
Before using the system, it is necessary to calibrate it. This means to know the parameters with which the images were taken, to study the acquisition geometry of the system and to check and verify the synchronization of the 4 integrated cameras.
To get this data, a Matlab tool ("Camera Calibrator" (Fig. 6)) was used which allows to obtain these parameters from images taken from the camera. For the procedure, checkerboards panels with known dimensions need to be used. In our case, they were attacked on a wooden panel to limit their deformations.

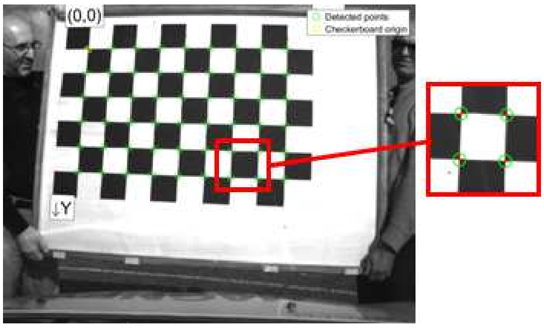

Fig. 6. Wooden panel with checkerboards for the camera calibration.

The procedure then suggests carrying out a series of photos of the panel from different points of view which can then be inserted in Matlab. 20 photos were made for each camera and the application made it possible to extract the parameters (Table 2).

Table 2. Estimated values of intrinsic parameters.

Calib. Param.	**Camera 1** [pixel]	**Camera 2** [pixel]	**Camera 3** [pixel]	**Camera 4** [pixel]
c	1646,5	1652.5	1646.8	1645.7
ξ_0	1393.4	1363.4	1375.2	1362.6
η_0	1798.9	1840	1837.1	1848.2
k_1	-0.348	-0.347	-0.346	-0.342
k_2	0.141	0.112	0.113	0.106

4 A case study

The area chosen as a test site is the ‘Campidoglio’ District in Turin, north-West of Italy (Fig. 7 left). This area is predominantly residential, located in semi-central location of the City, and characterized by the presence of commercial facilities, as well as various public places and services, such as schools. The activities were aimed to the implementation of a medium-scale 3D metric documentation of a block of the 'Campidoglio' district (Fig. 7 right) by means of terrestrial laser scanning survey with the capabilities to associate pollution data. The generated 3D model can be used as reference for the spatial information which will be structured in an interoperable database.

Fig. 7. The Campidoglio district (left) and the buildings block selected for the analyses (right).

This test site was selected for different reasons:

- it has lots of features: buildings, schools, roads, cycle and public transport paths;
- it is rounded by streets having different kind of traffic intensity (from one-direction street to multiple lanes avenues, part of the principal traffic artery of the city);
- it is possible to easily survey the district by bike;
- the air pollution can change significantly during the day according to the work and school time. So it can be very useful to monitor the pollution behavior along different times of the day;
- the area is full of stable features useful to create a good reference 3D model and acquire laser scanner and imaging data.

The activities described below refer to a fist acquisition made to test the system, the available sensors and the implemented structure for the storage and management of the data in a spatial database.

4.1 Data acquisition and processing

The beginning steps have involved the construction of a topographic network composed by five vertices (Fig. 8 red). The survey was made through a GNSS double frequency and multi-constellation receivers in static modality standing on each point for about 1 hour, since in that place the GNSS coverage was not so good.

The coordinates of these points were determined in a post-processing approach, considering a single-base solution (through the Leica Geo Office® software v.8.3) with the Torino permanent station of the Regione Piemonte CORSs (Continuous Operating Reference Stations) network as reference. The coordinates were estimated with a high level of accuracy (σ_M = 3 mm) and the phase ambiguity was fixed for all points, which has guaranteed a high level of precision for the georeferencing step.

Starting from the reference network, it was possible to acquire the position of some reference points (markers, Fig. 8 blue) through the use of a total station and a prism. All measurements were subsequently adjusted with the MicroSurvey StarNet v.7.0 software, in order to obtain the final coordinates: the root mean square (RMS) of the estimated coordinates is less than 1 cm.

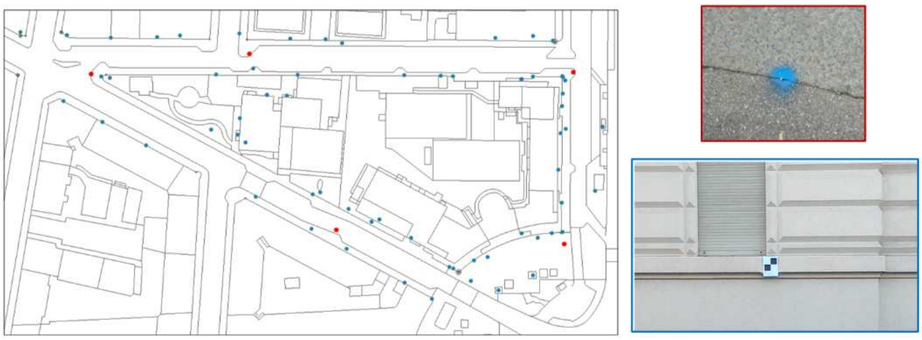

Fig. 8. Vertices distribution along the area (red) and position of the markers for the laser data georeferencing (blue). On the right, two examples of the used points: a network vertex (top) and a paper marker (bottom).

Then, terrestrial laser scanning surveys were performed to obtain a reference model for the pollution spatial information. The georeferencing of the scans took place through the pre-signalization of the markers measured by topographic techniques.

To cover the entire block, 14 scans were acquired using the laser Faro Cam2 Focus 3D (Fig. 9). It is a system with a range of acquisition from 0.6 m to 130 m, that is also able to acquire images through an integrated camera in order to color the point cloud. Each scan was acquired with 1/4 of resolution (÷ 1 point every 7mm at 5 m), it requires about 7 minutes for cloud acquisition and 1 minute for images collection.

The laser data were processed using Scene version 5.2, which is the own software developed by FARO. The process follows these steps:

1. scans integration and visualization: it is the first step where the scans can be visualized in the project space;
2. scans georeferencing: the software has an internal database that allows to automatically detect the markers in the cloud. Since the markers were topographically acquired, it was possible to insert in Scene their coordinates in the chosen reference system and georeferenced the whole model. To assess the registration reliability, it is possible to have a look to the errors contained in the ScanFit report;

3. data filtering and coloring: sometimes unnecessary data are recorded, but they can be manually deleted in order to reduce the point cloud and to facilitate the data processing. Then the point clouds can be colored through the acquired images.

The elaboration required about 7-8 hours for the entire process (PC: Windows 7, Intel Core i7, 8 GB RAM) and the result is a colored 3D points cloud composed by 300 million points (Fig. 9).

Fig. 9. Final 3D model generated through the laser scanner technology (FARO FOCUS 3D at the bottom right of the image).

For the imaging and environmental data (described above in the paragraph 2), a cargo bicycle was adopted to house all the sensors (Fig. 10).

Fig. 10. Acquisition system equipped with all the imaging and environmental sensors.

The acquired spherical images were processed with the commercial software Agisoft PhotoScan that allows, quickly and easily, to obtain three-dimensional models from images. The photos were initially aligned, founding correspondences between them to determine their position at the time of acquisition, and a first point cloud was generated. Subsequently, the dense cloud was realized. It has allowed to obtain a more detailed description of the area as reported in the final cloud shown in Fig. 11.

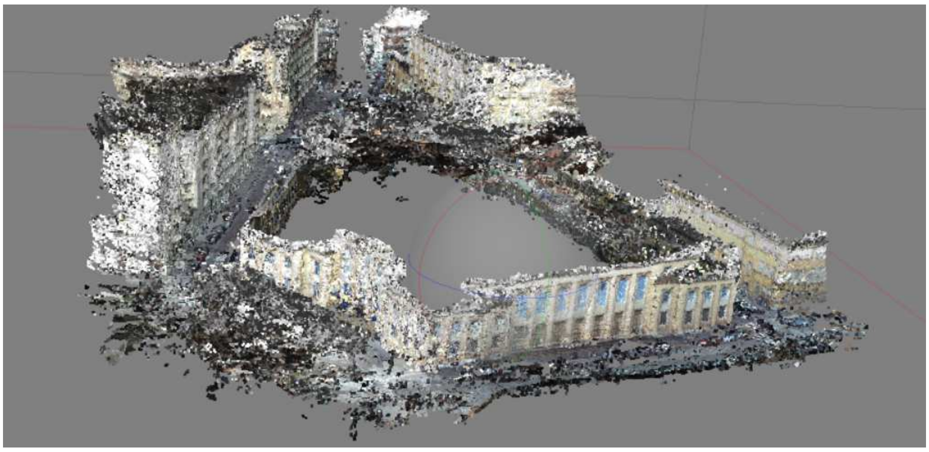

Fig. 11. Final 3D model generated through spherical images in the PhotoScan software.

4.2 Management of dynamic data in GIS

The data obtained from the used sensors (Fig. 12) were structured on a dynamic spatial database for the management of air quality data. It is based on a data model compliant with the OGC CityGML standard [17, 18], with a proposed extension for what concerns the dynamic environmental parameters. The open source GIS platform (based on PostgreSQL/PostGIS, QGIS) is able to perform the pre-processing steps to integrate the acquired data, to store the data, to be able to carry out real-time analysis, and to perform analysis to estimate the qualitative indicators of air quality.

The database schema chosen for building the GIS is an extension of CityGML for representing the information about air quality: the CityGML Air Quality Application Domain Extension (AQADE) [2]. A synthesis of the CityGML extension is shown in Fig. 13. Analyzing the monitored data in association with their location in the 3D city model and further parameters (such as traffic at the moment of the survey, building usage, heating periods and so on) it could be possible to do some considerations (e.g. what are the main sources of air quality pollution and what are the main affected objects). This information can be stored in the database compliant with CityGML AQADE model, remaining as documentation for some kind of decision by administrators, operators, researchers or simple citizens.

Fig. 12. Air quality data acquired by the sensors mounted on bikes. The red dots represent the acquisition points of the data concerning the air quality.

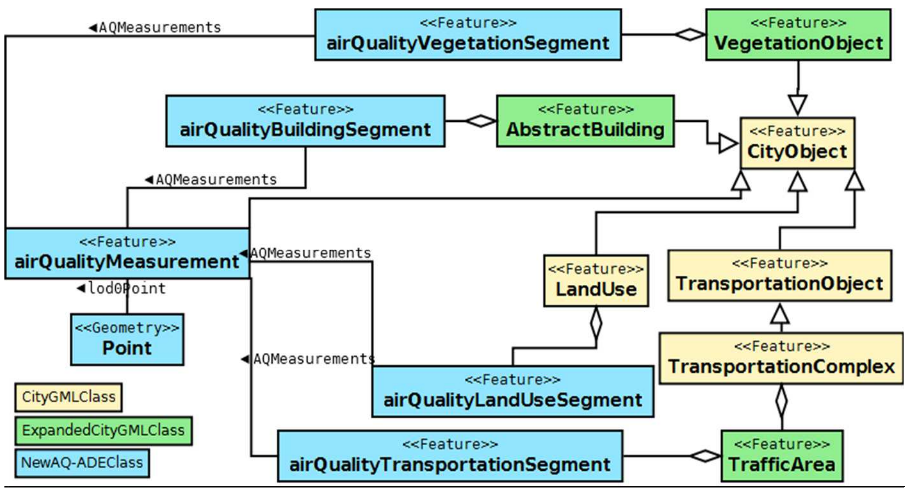

Fig. 13. The general UML schema of the CityGML AQADE.

It is possible to manage the so-structured data using different strategies. In particular, the first alternative is to use GML in order to represent and share the data; this can offer the advantage to maintain the object-oriented structure of the GML models and not to lose definition in the data complexity and interconnection. Moreover, the possibilities to manage the 3D data are wider. On the other hand, the tools to manage and analyze dynamic data in GML are still in a development phase, and the so-structured wide datasets could result computationally heavy.

The second strategy has been used here: the translation of the model in an SQL database. The passage to an object-relational model permits to manage in an easier way the data, maintaining some important relations. For the management of the data in the so-structured database PostgreSQL-PostGIS was used, and QGIS was used as a GIS software tool as a support for both a graphical interface and analysis tools.

The information can be managed, visualized and analyzed in GIS for obtaining useful information (statistics, spatial queries). Moreover, a map of the pollution of the city can be generated by the interpolation of the measured points [2] (Fig. 14).

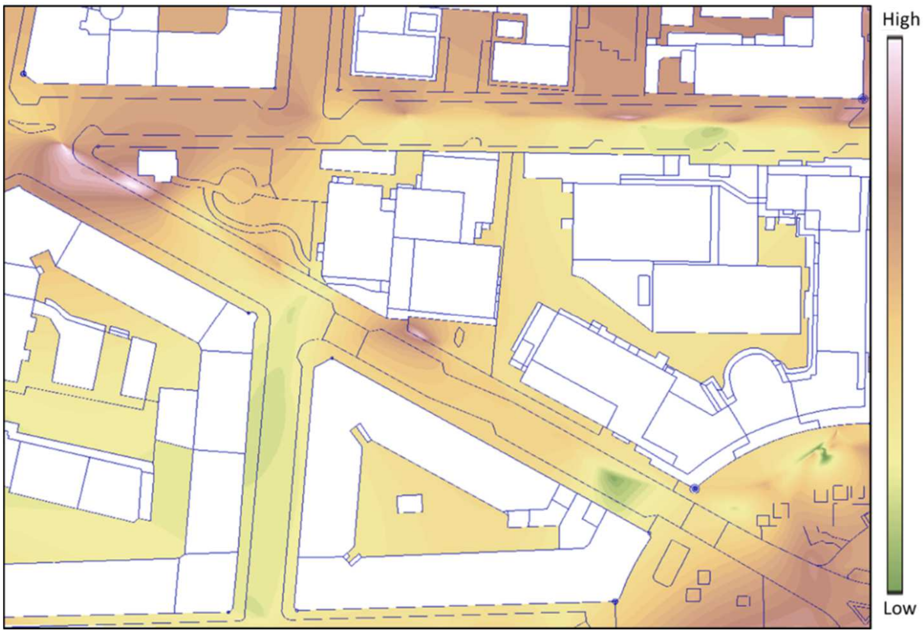

Fig. 14. Generation of the map of the presence of particulate (PM 2.5) in the study area, deriving from the interpolation of the measured values conducted on the GIS platform, using the method 'Inverse Distance Weighted' with power 2, as was tested in previous researches [2].

5 Conclusions

The proposed system allows to survey the 3D geometry of the city using mobile and low-cost sensors. This is very helpful for rapidly and accurately updating the maps (both from the geometrical and the semantic points of view). Moreover, the acquired information can be effectively managed in standardized GIS, useful for supporting a number of queries and analysis for different aims.

The main benefits of the tested acquisition system for pollution data are: negligible production of pollutants; limited alteration of the sensed environmental data (i.e., ground dust and ozone levels) due to the low speed of the bicycle (i.e., ~15 km/h); possibility to collect data from different locations without additional costs if the devices are mounted on bicycles of a bike-sharing system or on private bicycles; cheapness. The main drawbacks are: lower accuracy than fixed, standard air quality sensors; exposure of the devices to physic shocks (e.g., holes and uneven ground), which can produce malfunction; sensibility of the sensors to atmospheric phenomena (e.g., rain, hailstorm, direct sunlight); risk of theft and vandalism. The low cost-per-device allow many nodes over the urban area to be deployed. Moreover, installing the devices on bicycles, these can be moved within the urban area without additional costs. Therefore, pervasive data distributed over the area of interest can be provided by the proposed system and the knowledge of the environment through the generation of a 3D model from images is fundamental to understand the pollution behavior in relation to fixed infrastructures along the area. The generated 3D model derives from the panoramic camera, but it can be extracted also from the webcam installed on the bicycles. This solution will be further analyzed to assess the reliability of images acquired with a very low-cost system easily replicable in multiple vehicles.

References

1. Anastasi, G., Bruschi, P., Marcelloni, F., 2014. 'U-Sense', A cooperative sensing system for monitoring air quality in urban areas. *Smart Cities*, 34.
2. Arco, E.; Boccardo, P.; Gandino, F.; Lingua, A.; Noardo, F.; Rebaudengo, M., 2016. An integrated approach for pollution monitoring: smart acquirement and smart information. In: *1st International Conference on Smart Data and Smart Cities*, 30th UDMS, Split (Croatia), 7–9 September 2016. pp. 67-74.
3. Bates, D.V., Bell, G.M., Burnham, C.D., Hazucha, M., Mantha, J., Pengelly, L.D., Silverman, F., 1972. Short-term effects of ozone on the lung. *J. Appl. Physiol.*, 32.
4. Dutta, P., Aoki, P. M., Kumar, N., Mainwaring, A., Myers, C., Willett, W., Woodruff, A., 2009. Common sense: participatory urban sensing using a network of handheld air quality monitors. In: *Proceedings of the 7th ACM conference on embedded networked sensor systems,* pp. 349-350.
5. Eisenman, S. B., Miluzzo, E., Lane, N. D., Peterson, R. A., Ahn, G. S., Campbell, A. T., 2009. BikeNet: A mobile sensing system for cyclist experience mapping. *ACM Transactions on Sensor Networks (TOSN)*, 6(1).
6. Fann, N., Lamson, A. D., Anenberg, S. C., Wesson, K., Risley, D., Hubbell, B. J., 2012. Estimating the national public health burden associated with exposure to ambient PM2. 5 and ozone. *Risk analysis*, 32(1), pp. 81-95.
7. Hasenfratz, D., Saukh, O., Sturzenegger, S., Thiele, L., 2012. Participatory air pollution monitoring using smartphones. *Mobile Sensing*.
8. Hasenfratz, D., Saukh, O., Walser, C., Hueglin, C., Fierz, M., Arn, T., Beutel, J. Thiele, L., 2015. Deriving high-resolution urban air pollution maps using mobile sensor nodes. *Pervasive and Mobile Computing*, 16, pp. 268-285.
9. Kheirbek, I., Wheeler, K., Walters, S., Kass, D., Matte, T., 2013. PM2. 5 and ozone health impacts and disparities in New York City: sensitivity to spatial and temporal resolution. *Air Quality, Atmosphere & Health*, 6(2), pp. 473-486.
10. Khedo, K. K., Perseedoss, R., Mungur, A., 2010. A wireless sensor network air pollution monitoring system. *International Journal of Wireless & Mobile Networks.* 2(2), pp. 31-45.
11. Lippmann, M., 1989. Health effects of ozone a critical review. *Japca*, 39(5), pp. 672-695.
12. Ma, Y., Richards, M., Ghanem, M., Guo, Y., Hassard, J., 2008. Air pollution monitoring and mining based on sensor grid in London. *Sensors*, 8(6), pp. 3601-3623.

13. Mansour, S., Nasser, N., Karim, L., Ali, A., 2014. Wireless Sensor Network-based air quality monitoring system. In: *Computing, Networking and Communications (ICNC), 2014 International Conference on,* IEEE, pp. 545-550
14. Piras, M., Dabove, P., 2016. Comparison of two different mass-market IMU generations: bias analyses and real time applications. In Position, Location and Navigation Symposium (PLANS), 2016 IEEE/ION (pp. 34-41). IEEE.
15. Pope III, C.A., Dockery, D.W., 1992. Acute health effects of PM10 pollution on symptomatic and asymptomatic children. *American Review of Respiratory Disease*, 145(5), pp. 1123-1128.
16. Postolache, O., Pereira, M., Girao, P. M. B. S., 2005. Smart Sensor Network for Air Quality Monitoring Applications. In: *Instrumentation and Measurement Technology Conference, 2005. IMTC 2005. Proceedings of the IEEE,* IEEE, 1, pp. 537-542.
17. Prandi, F., De Amicis, R., Piffer, S., Soavea, M., Cadzowb, S., Boix, E. G., D'Hondt, E., 2013. Using CityGML to deploy smart-city services for urban ecosystems. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 4.
18. Soave, M., Devigili, F., Prandi, F., de Amicis, R., 2013. Visualization and analysis of CityGML dataset within a client sever infrastructure. In: *Proceedings of the 18th International Conference on 3D Web Technology,* pp. 215-215.
19. Spektor, D. M., Lippmann, M., Lioy, P. J., Thurston, G. D., Citak, K., James, D. J., Hayes, C., 1988. Effects of ambient ozone on respiratory function in active, normal children. *American Review of Respiratory Disease*, 137(2), pp. 313-320.
20. Tsujita, W., Ishida, H., Moriizumi, T., 2004. Dynamic gas sensor network for air pollution monitoring and its auto-calibration. In: *Sensors, Proceedings of IEEE,* IEEE, pp. 56-59.
21. Velasco, A., Ferrero, R., Gandino, F., Montrucchio, B., Rebaudengo, M., 2015. On the design of distributed air quality monitoring systems. In: *11th International Conference of Computational Methods in Sciences and Engineering (ICCMSE 2015),* Athens (Greece).