City-Wide Mobile Air Quality Measurement System

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Abstract— **In this paper we present an air quality measurementsystem that can be used to generate a map of the air quality in acity. The system is made of stations that can be attached to busesand taxis and gather data about air quality along the day as they travel in the city. Each station has sensors to measure the concentration of different gases, a position sensor (GPS) and a GSM/GPRS communication module to transmit the data to a central server. Each station is self-sufficient in terms of energy through the use of a battery and solar panels. The data server can be accessed through the internet using a browser and presents the results in real time overlapped onto a Google map of the city indicating, with different colors, the concentration ofeach measured gas (CO, NO_2, O_3, SO_2, and CO_2).**

INTRODUCTION

One big concern for people living in crowded cities aroundthe world is the quality of the air they breathe. Poor air qualityis mainly due to combustion engine vehicles although other sources can contribute to it like factories, airplanes and waste incinerators. Air pollution causes deaths and respiratory diseases [1], [2].

Many cities, nowadays, have air quality measurement stations that monitor the air quality in different points aroundthe city along the day and make the information accessible tothe general public in the internet [3]-[6]. This information is,however, limited to the location where the monitoring stationsare installed. In this paper we present a system which is madeof mobile stations which measure the air quality in real time.Each station, besides measuring the concentration of differentpollutants, is able to associate it with a time and position givenby a GPS unit and to send it in real time to a computer usingexisting mobile phone networks. It is solar powered which makes it completely mobile and able to work continuously forlarge periods of time.

Several mobile stations can be installed on the top of busesor taxis that roam the city. Using the information gathered, itis possible to build a map of the pollution around the city in real time. Another advantage is the capability of easilymonitoring the air quality in a given place where there is nofixed air quality monitoring station.

Those that contribute in a systematic way to the increasethe gases concentration, such as public transport or trucking companies, should be the first to monitor their emissions andto take corrective actions. The construction of gardens in polluted zones, the change of traffic routes or a more seriousmanagement of the architectural and industrial park of a citycan considered to minimize the pollution problem. However, it is only possible to take concrete actions with accurate data obtained during different hours, days and seasons. For that, it's necessary to have an extensive monitoring system, capable of covering large zones and not only a small location, wheredata obtained cannot be generalized. A mobile station to measure air quality, easily integrated on a public transport fleet, can be a first step to achieve these goals.

In this paper a mobile station to measure air quality is described and the results obtained in the city of Lisbon, Portugal, with the implemented prototype are presented.

AIR QUALITY

In a general way, it is possible to describe the atmosphereas a very thin gaseous film, where all the meteorological phenomena that regulate the human life occur. Filled with a great diversity of molecules (Table I), the atmosphere performs, at the same time, a role of protection and regulation.

Air pollution can have various definitions. According to [1], "air pollution means the presence, within the external atmospheres, of one or more contaminants, or its combinationin quantities or with a temporal duration that can become harmful to human life, vegetable, animal or goods. The air contaminants include smokes, steams, paper hashes, dusts, soot, carbonic smokes, gases, fogs, radioactive material or toxic chemical products."

Certain atmospheric pollutants react with each other creating others pollutants called secondary pollutants. The dissociation, trough the sun's effect, of volatiles organic compounds, carbon monoxide and nitrogen oxide, produced by automobile's motors, lead to the formation of ozone, essentially during the summer, when temperature reaches higher levels.

TABLE I.   AVERAGE COMPOSITION OF PURE AIR.

Element	Symbol	Proportion
Nitrogen	N_2	78.084 %
Oxygen	O_2	20.946 %
Argon	Ar	0.934 %
Carbon dioxide	CO_2	340 ppm
Neon	Ne	18.18 ppm
Helium	He	5.24 ppm
Methane	CH_4	1.5 ppm
Krypton	Kr	1.14 ppm
Hydrogen	H	0.50 ppm
Oxide Nitrous	N_2O	0.40 ppm
Xenon	Xe	0.09 ppm

Air pollution has dramatic consequences for human health, leading to respiratory problems and even death [6] and for the environment like the greenhouse effect, acid rains and ozone layer reduction [7].

The European Community has dedicated special attention to the problem of the most representative pollutant's concentration, such as the case of Carbon Monoxide (CO), Nitrogen Dioxide (NO_2), Sulphur Dioxide (SO_2), Ozone (O_3) and particles of 10 µm or less (PM_{10}) and special Regulations have been produced.

Although the Carbonic Dioxide (CO_2) isn't considered a pollutant, its concentration has also to be quantified, due to importance of this gas to the planet's ecosystems.

The system presented here is capable of measuring the following gases in the atmosphere:

- Carbon Dioxide (CO_2) – *Carbon Dioxide is a gas essential to life in the planet, because it is one of the most important elements evolving photosynthesis process, which converts solar into chemical energy. The concentration of CO_2 has increased due mainly to massive fossil fuels burning. This increase makes plants grow rapidly. The rapid growth of undesirable plants leads to the increase use of chemicals to eliminate them.*

- Carbon Monoxide (CO) – *Carbon Monoxide is a colorless and odorless gas. It is mainly due to automobile traffic, industrial activity and volcanic eruptions. This gas affects cardiovascular and nervous systems and, in large concentrations, inhibits the blood's capacity of exchange oxygen with vital organs. In extreme cases, may provoke death by poisoning.*

- Sulphur Dioxide (SO_2) – *Sulphur Dioxide is a colorless gas, detectable by the distinct odor and taste. Like CO_2, it is mainly due to fossil fuels burning and to industrial processes. In high concentrations may cause respiratory problems, especially in sensitive groups, like asthmatics. It contributes to acid rains.*

- Nitrogen Dioxide (NO_2) – *Nitrogen Dioxide is a brownish gas, easily detectable for its odor, very corrosive and highly oxidant. It is produced as the result of fossil fuels burning. Usually NO thrown to the atmosphere is converted in NO_2 by chemical processes. In high concentrations, NO_2 may lead to respiratory problems. Like SO_2, it contributes to acid rains.*

- Ozone (O_3) – *Ozone is a colorless and highly oxidant gas present at low levels of the higher layers of the atmosphere (troposphere). It is the result of a chemical reaction evolving organic pollutants, nitrogen oxides and solar radiation. Usually, it is denominated as a secondary pollutant. Ozone is responsible for the so- called photochemical smog and is often pointed out as the main cause responsible for agricultural losses. There are vegetal species particularly sensitive to its effects. In humans it can irritate the respiratory tract and cause breathing difficulties.*

The prototype station build is capable of measuring thesefive gases and can be upgraded to include the measurement ofmore gases and small airborne particles concentrations.

In Portugal the Government has defined some guide values and limits of concentration of pollutants in the atmosphere [10]. According to these information and [11], it was possibleto build a table (Table II) which qualifies the air quality, giventhe concentration of these pollutants. There is no universal airquality index. Other organizations and countries have definedtheir own indexes (see [7] for the case of the United States ofAmerica).

I. MOBILE STATION HARDWARE

A. Station's Main Structure

In order to build a mobile, autonomous and automatic device, capable of measuring the concentrations of different gases that contribute to pollution, several modules had to be designed and integrated into a single system (Fig. 1). Those modules are:

- Control module;
- GPS module for station location;
- GSM/SPRS module for data transmission;
- Battery and photovoltaic cells for autonomous operation;
- Sensors for each gas to be monitored;
- Sensors for temperature and movement;
- Temporary data storage.

Class	CO [µg/m³][PPM]		NO₂ [µg/m³][PPM]		O₃ [µg/m³][PPM]		SO₂ [µg/m³][PPM]	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Bad	10000 [8.7290]	-----	400 [0.213]	-----	240 [0.1223]	-----	500 [0.1908]	-----

Weak	8500 [7.4197]	9999 [8.7281]	230 [0.122]	399 [0.212]	180 [0.0917]	239 [0.1218]	350 [0.1336]	499 [0.1906]
Average	7000 [6.1103]	8499 [7.4188]	140 [0.074]	229 [0.122]	120 [0.0611]	179 [0.0912]	210 [0.0802]	349 [0.1332]
Good	5000 [4.3645]	6999 [6.1094]	100 [0.053]	139 [0.074]	60 [0.0306]	119 [0.0606]	140 [0.0534]	209 [0.0798]
Very Good	0	4999 [4.3636]	0	99 [0.053]	0	59 [0.0301]	0	139 [0.0531]
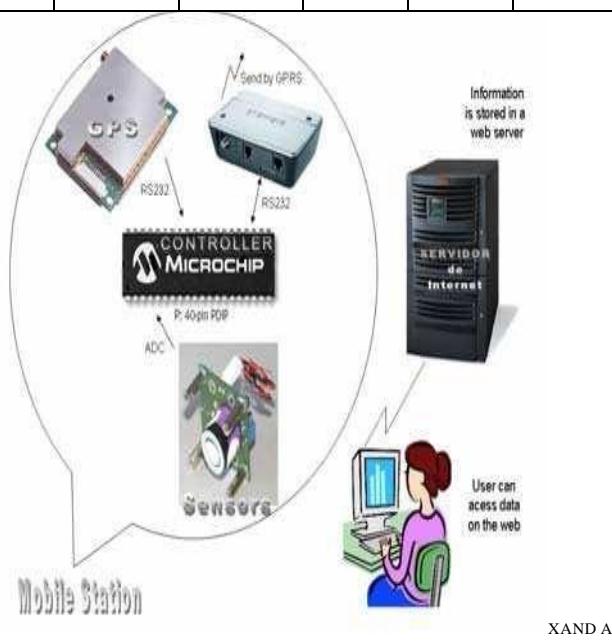
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Figure 1. Block diagram with the system components.

The information obtained from the sensors is sent to a server's database with Internet connection. The mobile stationtransmits to this server through a GSM/GPRS module and uploads the data. The database can be accessed with a browserprogram on an internet page which presents some generic information about the station status, displays the concentration ranges of the gases and allows the system administrator to perform some database maintenance services. Anyone can access the database and see graphically all the information ofthe measured values and their tracking for a given day. Theseinformation is color coded based on the gases concentration allowing an easy evaluation of the air quality. For each location, the specific concentration of each gas, time and dateat which the data was acquired and the local temperature recorded at that moment are displayed.

B. *Control Unit*

A 16-bit microcontroller from Microchip, model dsPIC30F4013, is the heart of the mobile station. It has 49 KBof flash memory, 30 digital input/output ports, 13 analog input ports with 12-bit resolution and interface circuitry for peripheral connection (UART, SPI and I^2C).

C. *Temperature measurement*

It is important to know the temperature at each location inorder to correct the values given by sensors which are highly temperature dependent. The temperature sensor also reads thetemperature inside the box, in order to control it with the helpof a fan used to extract the hot air from inside the station. Thesensor used was model MCP9701A from Microchip. It has anaccuracy of 0.5 ºC in the range from 0 to 50 ºC. The analog output's sensitivity is 19.53 mV/ºC.

D. *Pollution Measurement Sensors*

Each gas concentration is measured with a different sensorfrom Alphasense. They were chosen due their low power consumption which is an important factor in a solar poweredsystem. From the available models the chosen ones were generally bigger to reduce the system cost although the use ofsmaller ones would allow a reduction in the total size of the mobile air quality measurement station. In Table III thecharacteristics of each gas sensor used are summarized.

TABLE III. CHARACTERISTICS OF THE GAS SENSORS FROM ALPHASENSE.

	CO2	**CO**	**NO2**	**SO2**	**O3**
Model	CO2-A1	CO-BF	NO2-B1	SO2-BF	CL2-B1
Range	100 ppm to 90 %	0 to 100 ppm	0 to 20 ppm	0 to 20 ppm	0 to 20 ppm
Response Time	2 - 4 min	30 s	60 s	30 s	60 s
Resolution		0.3 ppm	0.02 ppm	0.1 ppm	0.02 ppm
Sensitivity	10 mV/ decade change	80 to 120 nA/ppm @400 ppm	-600 to -1100 nA/ppm @ 10 ppm	300 to 440 nA/ppm	-700 to -1100 nA/ppm (10 ppm)

The signal conditioning used for the carbon dioxide sensor(CO_2) is an instrumentation amplifier powered by ±5 V (Fig. 2). The sensor voltage output ranges from 0 to 15 mV. The amplifier gain used was 100 leading to an amplified voltage between 0 and 1.5 V.
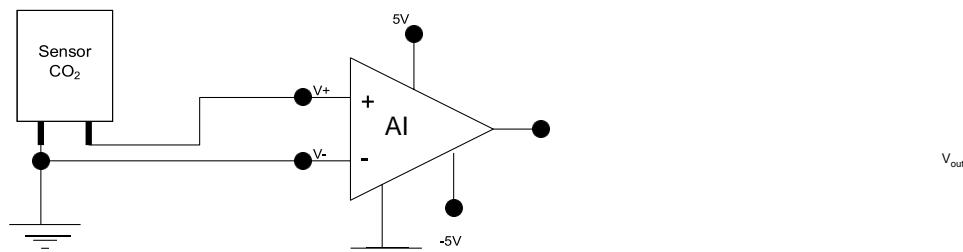
Figure 2. Signal conditioning of CO_2 sensor.

The other sensors are amperimetric ones. Alphasenseprovides a signal conditioning board for these sensors (Fig. 3).These boards are powered with 9 V and the gas concentrationinformation is given by the current they consume. This current, which can be adjusted, ranges from 4 mA (nullconcentration) to 20 mA (maximum concentration).

To convert this current to a voltage a 50 Ω sampling resistor (0.01 % accuracy) and an instrumentation amplifier with a 4.95 gain (Fig. 4) were used. The output voltage (v_{out})ranges from 0.99 V to 4.95 V.
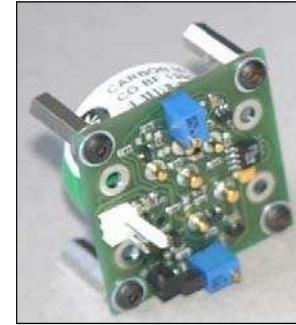
Figure 3. Photograph of an Alphasense signal conditioning module for oneof their carbon monoxide sensors.
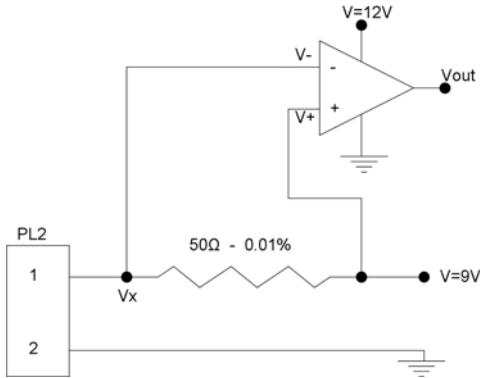
Figure 4.   Signal conditioning for the amperimetric sensors.

E.   Data Transmission System – GSM/GPRS Module

The automation of data acquisition and of data transmission represents an essential feature of the mobile station. With it, the station doesn't require any user intervention to acquire, store and transmit data since it automatically sends the data to the server where it can be easily read.

The system uses a low cost GSM/GPRS module from Siemens, model TC65, with integrated TCP/IP stack, which turned the system development to an easy task. It was connected to the microcontroller using a RS232 protocol.

F.   Positioning System – GPS Module

The mobile station moves around permanently and acquires data in different locations, so it needs a GPS receiverto track its geographical location. The receiver gives a position relative to the Earth, referenced to the Equator, the Greenwichmeridian and sea level. It is given by three parameters:latitude, longitude and altitude.

The receiver module used, made by Garmin (model 15H),was chosen due to its low cost, small size (36×46×9 mm) andlow power consumption (390 mW). It has a fast acquisition rate, namely 2 s for reacquisition, 15 s for warm start and 45 sfor a cold start. The position accuracy is 15 m which is not thebest in the market but which was considered adequate for thisapplication.

G.   Additional Memory – EEPROM

Due to the amount of data the station needs to store, evenin power failure situations, the system was fitted with a non-volatile memory EEPROM with 1 Mb capacity and an SPI interface. It is powered with 5 V and consumes less than7 mA.

H.   Movement Sensor

The system is equipped with a movement sensor, which detects small mechanical vibrations and converts it to electric impulses. The station turns itself off when it senses it is stopped for more than a defined amount of time, in order to save energy. When the sensor detects movement the station comes back from sleep mode.

I.   Power Source

The station is equipped with a photovoltaic system constituted by two panels, a solar charge controller and a battery (Fig. 5) in order to guarantee its own energy generation and to be completely autonomous.
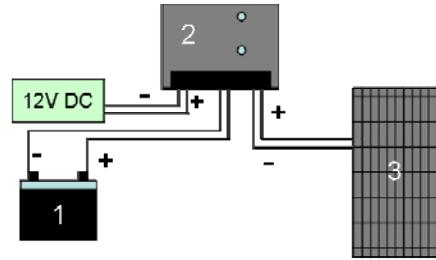

Figure 5. Diagram of photovoltaic system used showing the battery (1),charge controller (2) and solar panels (3).

The solar panels convert energy from the sun into electricenergy. These devices are composed by photovoltaic cells. Each photovoltaic cell produces a small amount of power anda solar panel aggregates several cells in order to get to producemore power (in series to increase current or in parallel to increase voltage).

Two monocrystalline solar panels, each with 16 cells andoccupying a 180×226 mm area (0.04 m^2) were used. Considering their 15.5% efficiency and the worst case average monthly solar radiation in Lisbon, Portugal, which is 63.6 W/m^2 in December, as depicted in Fig. 6 [12], the average generated power is 390 mW. If we consider theannual solar radiation average of 185 W/m^2, we have an annual average 1.14 W power supply. It is estimated that the station works only about 15 hours a day. The rest of the time itis in standby mode. The power consumed in the normal modeis 1044.75 mW and the power consumed in standby is 174 mW. The GPRS module consumes 2076 mW and works for about 8 minutes in each hour. Using these values the average power consumed by the station is 729 mW. Using justtwo solar panels is not enough for the station to have enoughpower in the months of November, December and January inLisbon, Portugal. It will be necessary to fit the station with two additional solar panels.
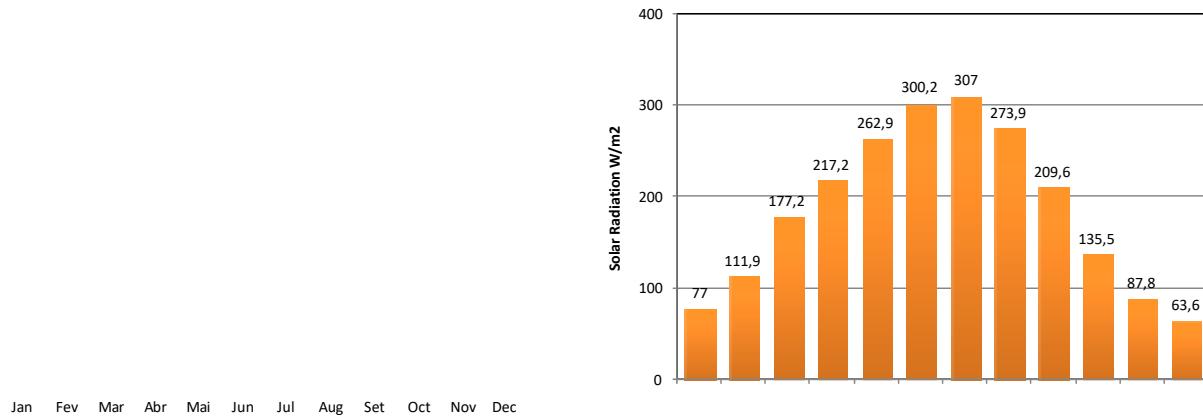

Figure 6. Average monthly solar radiance in Lisbon, Portugal [12].

The mobile station has a battery that converts chemical energy into electric energy, thus giving it the needed power any time of the day. This battery used was a 12 V sealed lead-acid with 2 Ah capacity. This type of battery was chosen because it is the most appropriate for applications where thereis a constant charging and discharging of the battery.

The solar charge controller used was from STECA, modelSolsum 5.0. It has overload protection, discharge protection and temperature compensation.

Fig. 7 shows the interior of the station with all modules connected and ready to operate.

J. *System Assembly*

The station has one printed circuit board which contains the microcontroller, sensor conditioning circuits, EEPROM memory, DC-DC converters to produce the different supply voltages required by the different modules of the station and relays to switch on and off the GSM/SPRS module. It was designed using Altium Designer and manufactured by Beta Layout. A photograph of the board after assembly is shown inFig. 8.

The underside of the station is glued to a magnetic pad which allows the station to be easily installed and removed from th   port it.
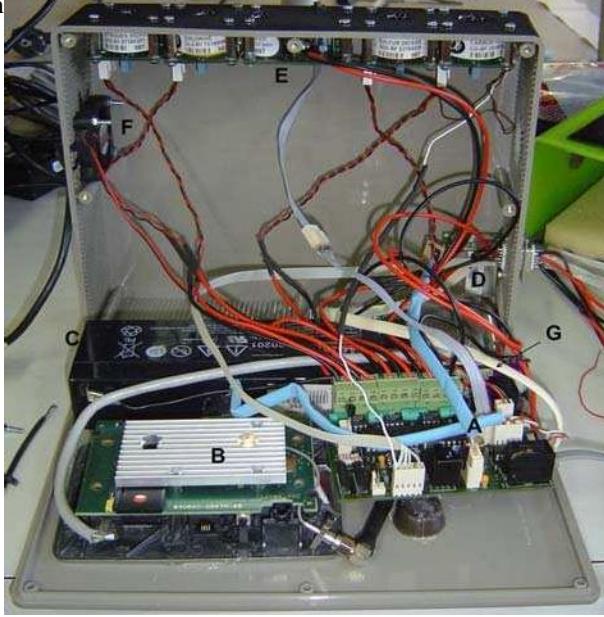

Figure 7. Interior of the station. Main Board (A). GSM/GPRS modem (B).Battery (C). GPS Module (D). Gas sensors (E). Cooling fan (F). Solar panel controller (partially covered by the main board) (G).
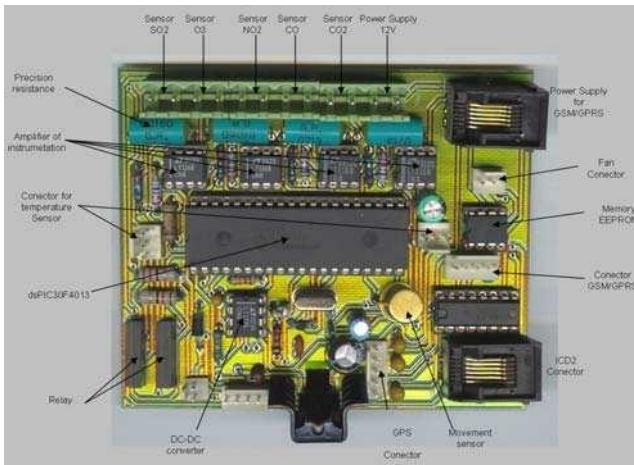

Figure 8. Main system board.

II. MOBILE STATION SOFTWARE

The software developed for this system is split into two parts – the station and the server. At the station level, the microcontroller firmware was developed in C using Microchip's MPLAB programming and debugging environment. At the server, software was developed using HTML, PHP and SQL.

A. *Station*

Each 200 m travelled, the microcontroller gets a sample ofthe value of each of the five gas sensors and the value of the temperature sensor. It also reads the information from GPS module and associates the position (in latitude and longitude)and time with the data previous collected. To keep the powerconsumption low, the gathered data is kept on an EEPROM until it is full and the GPSR module is turned on and the datais send to the server. This way the GPRS module is poweredoff most of the time leading to important energy savings.

```
POST /add.php HTTP/1.1
Accept: image/gif, image/x-xbitmap, */*
Accept-Language: en-gb,pt;q=0.5
Accept-Encoding: gzip, deflate
User-Agent: Mozilla/4.0 (compatible)
Host: localhost:79
Connection: Keep-Alive


aa=150323021007123456781234566789…. &b=15052
1512323465234….&c=135322345…
```

Figure 9. Example of a header and body of the message.

The data is sent via HTTP, using the POST method. The data is sent in the body of the message, using several variables, each with 1810 bytes. The different variables in thebody are separated by a character "&": This scheme adopted ispresented in Fig. 9.

B. *Server*

The server used was a desktop computer with permanentInternet connection. It runs Microsoft Windows XP and had Apache server software installed. An SQL database is used and web pages were created using PHP.

For the purpose of data visualization, a page on theInternet has been created as depicted in Fig. 10. On this pageone can see, not only the measurements obtained, but also themobile station location and an exhibition of air quality index.To analyze the measurements made, it is possible to choose aspecific time and date.

Figure 10. Example of server web page.

After choosing these items a map with colored dots wheremeasurements were taken can be depicted (Fig. 11). For eachof these locations the concentrations obtained for the selected gases can be presented. Google Maps were used through their application programming interface (API). This data was collected with the prototype installed on the roof of a privatelyowned automobile for testing purposes.
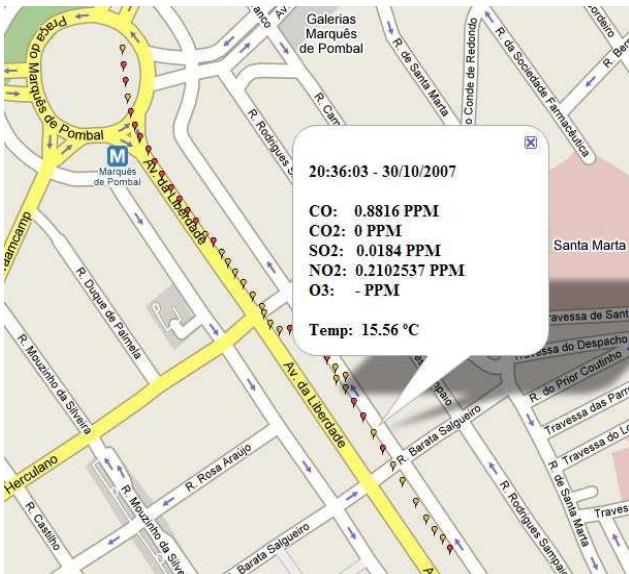

Figure 11. Extract from the Web page presenting the locations wheremeasurements were taken.

CONCLUSION:

In this paper a mobile station for air quality measurementis presented. It measures different gas concentrations and automatically sends the results to a server in the internet usingexisting mobile communication networks (GSM). It has a GPS In this paper a mobile station for air quality measurementis presented. It measures different gas concentrations and automatically sends the results to a server in the internet usingexisting mobile communication networks (GSM). It has a GPSfor figuring out time and position, a battery and solar cells for power generation, and the ability to store data so that the station can work on its own. It can run nonstop for days with only short breaks for repair.

A prototype was built to show that such a system was possible and to test how it would work. It's a place to start building a mobile network that can be used to make a picture of a city's air quality by using public transportation, for example. So far, it's worked as planned, but it's always being tried to see how well it's doing and where changes can be made.

It's better than current fixed stations in a number of ways. Being able to easily check the air quality in real time from anywhere and finding polluted areas that can be fixed is made possible by this technology. For example, it could be used to tell people about the

air conditions where they live and work.It would be great if the movable stations could be made in large numbers so that the air quality picture of a city could become a reality.

Most air quality monitors can pick up on other gases as well as the gas they are supposed to measure, but not as well. If more than one sensor with different sensitivity is used at the same time, this problem will be less severe. By combining the data from

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IEEE member Edward J. Wolfrum, along with Robert M. Meglen, Darren Peterson, and Justin Sluiter, wrote an article in the IEEE Sensors Journal in December 2006 called "Calibration transfer among sensor arrays designed for monitoring volatile organic compounds in indoor air quality." The article can be found on pages 1638–1643.