A mobile environmental sensing system to manage transportation and urban air quality

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***Abstract*—This work presents an integrated mobile environmental sensing and analysis system developed to support the management of transport and urban air quality. A novel spectroscopic UV sensor is employed to provide second-by-second measurements of multiple pollutants at ppb levels. Sensor nodes are deployed on vehicles, infrastructure and people and feed data into a dynamically configurable e-science computing platform that scales to support both near real-time incident management and longer term strategic planning decisions. This paper describes the system architecture and sensor node design alongside results from system development testing. It goes on to highlight avenues for future development and the potential for further applications involving the wider sensors community.**

I. Introduction

Human exposure to air pollutants including sulfur dioxide (SO_2), ozone (O_3) and nitrogen oxides (NO_x) is a serious and increasing health risk in many parts of the world [1]. Acute exposure episodes are especially prevalent in the urban environment where road traffic is a significant source of pollution [2]. Appropriate monitoring of the atmospheric conditions, combined with interventions in traffic management and the provision of traveler information can help to mitigate these problems [3]. The MESSAGE system consists of a mobile, wireless sensor network integrated with a high-performance computing architecture to provide high-resolution monitoring with broad geographic coverage and timely provision of information.

Urban pollutant concentrations are primarily a function of the local source emission rates from both mobile (e.g. vehicle tailpipe emissions) and static sources (e.g. local industries). Traditional assessment involves the long-term average modeling of these sources combined with relatively sparse networks of fixed monitors (such as the London Air Quality Monitoring network) with measurement protocols defined by the current air quality legislation. However, isolated studies have indicated that the pollutant concentrations within a street [4] may vary by an order of magnitude over the space of a few meters and over the period of a few seconds. Moreover, pollution hotspots have been associated with traffic management interventions (e.g. signalized junctions) and alternative control strategies can be shown to have an impact on pedestrian exposure levels [3]. Consequently there is a need for traffic management strategies to be derived with environmental objectives in mind. However, this imposes the need to monitor traffic, weather and pollutant concentrations at far higher spatial and temporal resolutions than currently available. MESSAGE seeks to exploit the opportunities provided by simultaneous advances in communications, positioning, computing, sensing and modeling technologies to develop a mobile, wireless environmental sensing network and data processing infrastructure to address this need.

This paper presents an integrated system architecture for the implementation of the MESSAGE system and the incorporation of a range of heterogeneous sensor devices. It goes on to describe the field units designed for implementation on in-service London Buses and the development of a novel differential UV absorption spectroscopy technique for the measurement of trace concentrations of urban pollutants.

II. System Architecture

A. Requirements and high-level architcture

In order to provide data describing urban pollutant concentrations at sufficiently high spatial and temporal resolution to address these needs, a network consisting of a large number of sensors is required. Vehicle and pedestrian-mounted mobile sensors allows the use of more intelligent sampling regimes, however this imposes practical constraints on the field unit designs, the technologies implemented by the constituent subsystems and the required data for full spatial and temporal referencing of all data.

Timely implementation of management strategies also requires frequent (e.g. every minute) updates of the system and may involve providing information to many users

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simultaneously. As a result of these constraints, a fully scalable data processing architecture has been developed.

B. A scalable, grid-enabled monitoring system

The computational environment for the MESSAGE project has been designed to handle the large quantities of data being sampled by a distributed array of mobile and static field sensors, ensuring that the captured data is available for real-time processing and visualization and is efficiently archived for subsequent historic analysis and modeling tasks (Fig. 1).

Managing the significant quantities of data coming from a large number of deployed sensors is a complex task. Sensors are connected via inherently unreliable wireless data connections (broken by tunnels, built-up areas, poor base-station coverage etc.) and will join and leave the network on a regular basis and in an unpredictable manner. Additionally, some sensors may only be active when their host vehicle is traveling between locations. As a result of this constantly changing sensor network fabric, different quantities of computing power are necessary to manage the network at any given point in time. To avoid the need to continually supply hardware resources to handle the theoretical maximum number of sensor nodes, we opt for a scalable approach using utility computing resources that are paid for only when required and can be brought online with a short lead time to efficiently manage fluctuations in required compute capacity.

Our architecture pairs sensors with sensor gateways. When a sensor joins the network, it contacts a known point of reference, a root gateway. This is a highly reliable master gateway that is always available at a known IP location and is supported by redundant replicas that can transparently replace the master root gateway in the event of a failure. This ensures that sensors joining the network can always contact a point of reference to announce their arrival on the network. A root gateway manages a group of sensor gateways that handle the high-throughput of data coming from a set of attached sensors. When a sensor joins the network, the root gateway looks at all the available sensor gateways and finds one with sufficient capacity to handle an additional sensor. Capacity management processes monitor the loading of gateways and can set up a new sensor gateway by starting a new, pre-configured, utility computing resource that will make a new sensor gateway available within a couple of minutes.

Once a sensor is paired with a sensor gateway, it streams pollution data readings to the sensor gateway which carries out any necessary pre-processing on the received data and then forwards it on to a data service that handles the storing of the data into a distributed Oracle database running on high performance database server resources.

C. Simulation of distributed compute platform

To support the ongoing testing of the system architecture, a simulator has been developed to generate virtual sensors that follow pre-determined routes, calculating their current position

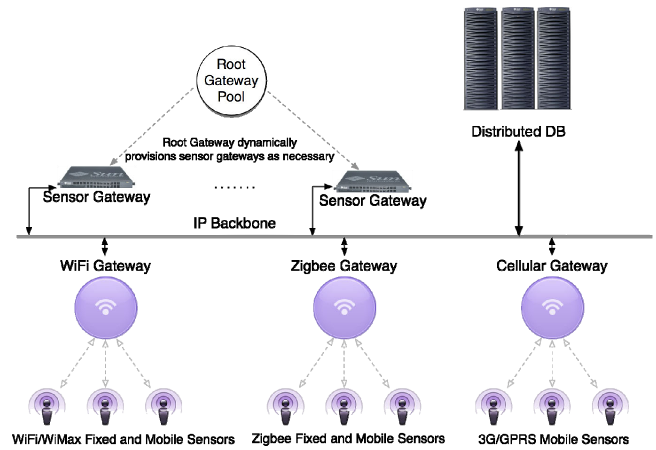

Figure 1. System comunications and hardware architecture

after each simulation time step and sending back random pollution values generated from a pseudo-realistic distribution. This permits the scalability of this system to be assessed by simulation of an arbitrary number of sensor nodes. Real-time visualization of the sensor network is currently provided via a Google Maps interface. The interface, shown in Figure 2. displays the position of sensors and historical data on the map display. Clicking on a sensor displays the most recent recorded data from that sensor. Real sensor devices are integrated into the map interface in parallel with the simulated sensors allowing parallel data capture from field sensor hardware an examination of alternative sampling strategies.

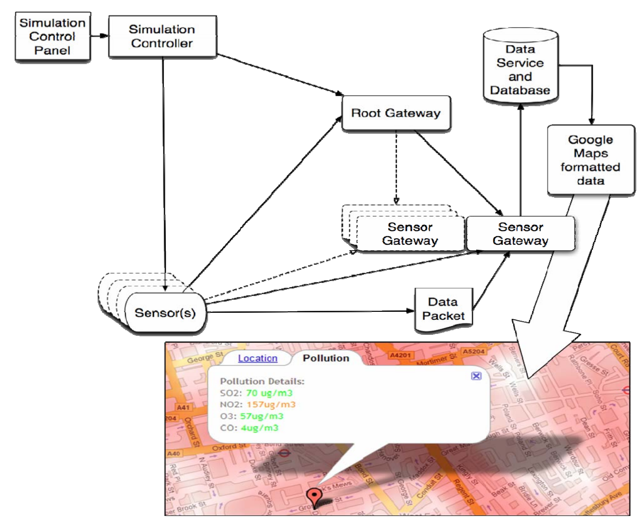

Figure 2. Simulation architecture and Google Maps-based sensor information interface

III. ENVIRONMENTAL SENSING PLATFORM

The computing architecture described above has been developed to support the heterogeneous range of sensors being developed in the project. In this section the MESSAGE field units developed at Imperial College London are described in more detail, with particular focus on the novel pollution sensing devices.

The MESSAGE Project is a three-year research project which started in October 2006 and is funded jointly by the UK Engineering and Physical Sciences Research Council and the UK Department for Transport. The project team, lead by Imperial College London, includes researchers at the Universities of Cambridge, Leeds, Newcastle and Southampton. The project also has the support of nineteen non-academic organizations from public sector transport operations, commercial equipment providers, systems integrators and technology suppliers.

A. Field unit design

Each of the MESSAGE field units incorporates several subsystems such that each sensor node may collate and transmit spatially and temporally referenced data packets (see Figure 3. 3). The Imperial Field Unit is being developed primarily for deployment on in-service London Buses and on associated infrastructure (e.g. bus shelters). The design therefore assumes that an external power supply is available and consequently a high-resolution optical sensing platform may be deployed.

The processing functions are implemented using an XScale processor running under Linux. This facilitates the inclusion of extensive processing at the sensor node to reduce communications traffic. Wireless communications are implemented using IEEE 802.11g devices in a Vehicular Ad Hoc Network (VANET) with GPRS cellular connectivity to support operation outside wireless zones. Spatial and temporal referencing is provided by the Positioning subsystem which implements an advanced combination of GPS, deduced-reckoning and map-matching and complimentary techniques using the communications signals to derive meter-level accuracies even in unfavorable conditions (e.g. urban street canyons). The processor, communications and positioning functions are integrated into a single compact unit that may accept inputs from a wide range of sensors. The novel UV absorption spectroscopy sensors employed in the current field units are described in detail in the following section.

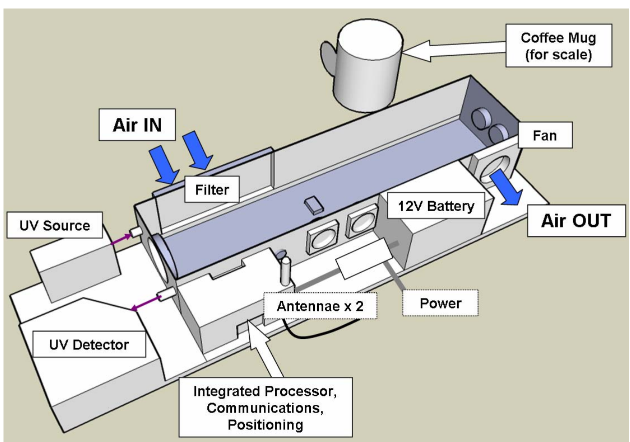

Figure 3. Field unit design showing constituent subsystems (Coffee mug included for scale)

B. Differential ultraviolet absorbtion spectroscopy

The volume mixing ratios of certain trace atmospheric gases may be determined using differential optical absorption spectroscopy (DOAS). This is a well-known method of retrieval within atmospheric science and has been documented comprehensively by a number of authors.

The custom developed DUVAS^{TM} method makes use of the characteristic narrow band absorption of the gas under study in the UV spectral range 200-300nm. These include SO_2, NO, NO_2, O_3, and Benzene, all of which are governed by strict legislative guidelines with respect to acceptable limits of ambient concentration. Please note that this list is not exhaustive and in fact many volatile organic compounds (VOCs) and poly aromatic hydrocarbons (PAH) are also detectible in this range if the instrument is suitable calibrated.

The Beer-Lambert law describes the absorption over a path length x (m) of photons by a gas with number density n (m^{-3}) and absorption cross-section $\sigma(\lambda)$ (m^2) and is usually written;

$$I(\lambda) = I_0(\lambda) F(\lambda) \exp[-\sigma(\lambda) n x - \alpha(\lambda) n x] \quad (1)$$

$$\begin{aligned}
&\textit{where} \\
&I(\lambda) = \textit{Measured Intensity (volts)}, \\
&I_0(\lambda) = \textit{Lamp Intensity (volts)}, \\
&F(\lambda) = \textit{Wavelength dependence of instrument (unitless)}, \\
&\sigma(\lambda) = \textit{Absorption cross section } (m^2), \\
&n = \textit{Number density } (m^{-3}), \\
&x = \textit{Pathlength } (m), \\
&\alpha = \textit{Scattering cross section } (m^2).
\end{aligned}$$

If we consider the intensity spectrum to be made up of broad (I_B) and narrow (dI) features, then we may write;

$$I(\lambda) = I_B(\lambda) \cdot dI(\lambda) \quad (2)$$

The narrow features (arising from trace molecular absorption) are then de-convolved from the spectrum and the resulting differentials are used to calculate the concentration (number density) of each absorber within the spectral range.

Figure 4. shows the sensor optical design. Light from a fiber-coupled UV source enters a modified White cell [5] and undergoes multiple passes between 3 spherical mirrors with the same radius of curvature. The path length is variable and is typically of the order 2-10 meters. Upon exit, the beam is focused and collected using a fiber optic 'light pipe' coupled to a spectrometer unit. The spectral output is imaged onto the surface of the CCD detector and intensity values are obtained via a 14-bit ADC to produce an atmospheric spectrum of diode number versus ADC counts (equivalent to wavelength versus intensity). At this point a further layer of analysis (the DUVAS^{TM} retrieval algorithm) is performed on the spectrum in order to 'disentangle' the multiple absorbing species and obtain separate mixing ratios for each pollutant simultaneously (see Figure 5.).

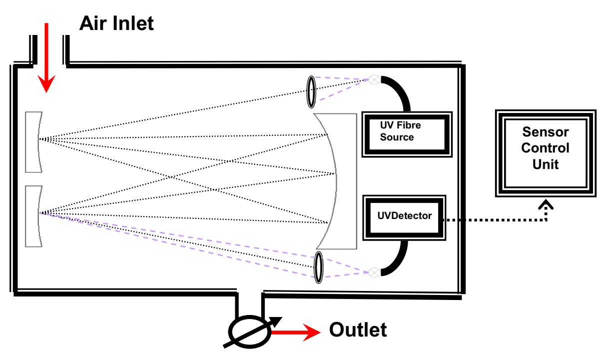

Figure 4. GUSTO sensor optical design schematic

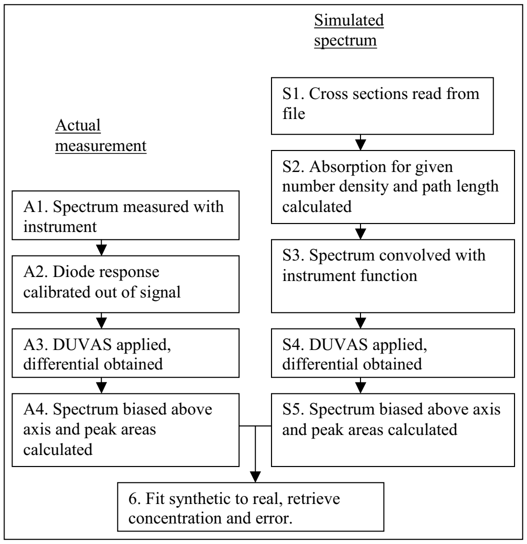

Figure 5. The DUVAS concentration retrieval process

It is worth noting that the entire process is extremely rapid and takes only a fraction of a second to perform - allowing for fast retrieval updates. This aspect becomes important when retrieving pollutant values in a rapidly changing dynamic atmosphere.

It is essential to ensure that each pollutant can be correctly detected by the system and that corresponding concentrations be accurately retrieved. To achieve this, three methods of sensor calibration are compared; 1) a known amount of gas is introduced into the system (known as physical determination); 2) conventional spectroscopic analysis that involves taking a sample scan and scaling against a measured background; 3) the DUVAS method is applied to the sample scan only. All three values should agree as the amount of gas present is the same regardless in each case.

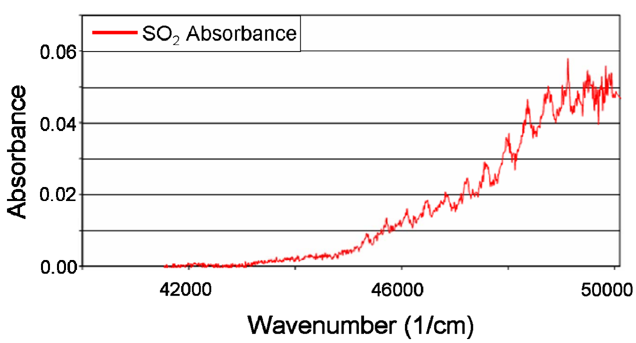

Figure 6. Measured absorbtion spectrum of 100 ppb SO_2

Figure 6. illustrates a typical absorption spectrum for SO_2 present at approx. 100ppb and Table I shows the general agreement between three calibration methods at this concentration. The physical method appears to have the greatest uncertainty as there are numerous sources of error associated with transferring trace quantities of gas into the optical path. Despite small discrepancies between the measured values, the low variability of the DUVAS method makes it a suitable basis for a standalone field unit where periodic calibration can readily accommodate constant errors.

TABLE I. COMPARISON OF POLLUTANT DETERMINATION METHODS

	Method	*SO_2 Concentration [ppb]*
1	Physical Determination using known gas quantity	102 (±12)
2	Spectroscopic Analysis against measured background	95(±4)
3	DUVAS differential retrieval algorithm	91(±1)

After the concentrations of all species have been determined in a real deployment situation (such as for MESSAGE), the on-board processor must decide whether to store, aggregate or transmit the data (or indeed perform a combination of all three) and this decision will be influenced by a number of factors including whether the value itself is of interest (such as an elevated pollution level), the sensor position relative to neighboring sensors, or system concerns such as the available power within the network.

IV. CONCLUSIONS AND FURTHER WORK

This paper has presented a mobile environmental sensing system developed to manage transport and urban air quality. Future work will include real world validation and deployment of the field units described in this paper in support of the MESSAGE Project field trials. The compute architecture and field unit design are entirely compatible with the incorporation of additional sensing devices and deployment to service other application areas. These opportunities will be explored as the project progresses in order to provide an enriched data set for various types of correlative studies with transport.

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