A Green Wireless Sensor Network for Environmental Monitoring and Risk Identification

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Abstract: A sensor-based community network suitable for periodic environmental data gathering and predictive analysis has been developed. Wireless sensors are used to form a mesh network for data reporting to a central site. This sensor network composed of Crossbow sensors aggregates and reconciles gathered information for environmental monitoring and risk identification. Data analysis and visual presentation is used in a geographical and temporal context. This network is considered green due to periodic data reporting from the sensor network, in contrast to the more common event-driven data reporting and treatment of each sensor as an independent system, removing the need for a global system clock and the associated synchronization. The removal of timestamp synchronization reduced the amount of communication required between network nodes, resulting in an overall energy saving, while not compromising the nature of the data gathered. The number of sensors deployed has also been set to be minimal for energy saving, while the spatial coverage is augmented through spatial interpolation with a geographic information system (GIS). The sensor network applications provide an outstanding representation of green networking, as sparse but sufficient environmental monitoring accompanied by real time data analysis and historical pattern identification permits risk identification in support of public safety and protection.

Keywords: wireless sensor, visualization, GIS

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1 Introduction

Wireless sensor networks can be vital predictors of future events which threaten species or environments. For example, event-driven information has been gathered from animal habitats (Szewczyk et al. 2004), volcanic activity monitoring (Werner-Allen et al. 2006) and environmental monitoring (Martinez et al. 2004). Wireless sensing in a densely populated urban community can be especially valuable for not only monitoring the physical environment, but also focusing on human impact to the environment and complex interactions within the community that are key considerations of a sustainable development. Actual deployment experiences in this regard, however, are limited and application development has been restricted (Lewis 2004). Previous work in sensors for structure monitoring (Zimmerman and Lynch 2006), urban flash flood awareness (Chang and Guo 2006), and mobile emissions monitoring (Cordova-Lopez et al. 2007) has been initiated, but with limited or non-existent data analysis.

Urban environments, such as those defined by campus, business, and other public spaces in our cities and towns, are interconnected with both well-being and our urban lifestyles. Consider truck routes which use main roads where children walk to school and pedestrians walk to work or shopping. Underpasses are used by passenger vehicles and pedestrians to cross train tracks and other traffic areas. These situations expose people to direct impacts due to the urban environment and its varied hazards. For example, vehicle emissions and air borne contaminates can impact air quality (Aldrin and Hogaek-Haf 2005) while roadways and underpasses can become flooded in the event of a sudden rainstorm (Ashley et al. 2005). Such events may occur routinely in some locations, have a rapid onset, or be a chronic or simply repetitive problem. A wide variety of impacts and interactions are possible within the complexity of an urban environment. In the smallest community of an urban university campus or industrial complex, buildings are heated or air-conditioned to create a comfortable living environment. Over-heating or over-cooling has been common in many such environments that lack green management or environmental control. In order to address these impacts and interactions toward an ultimate goal of a greener or more sustainable environment, direct investigations are needed to provide *monitoring* and *assessment* of key elements and features that may be used *to better understand the systems involved*. From such information, policy makers and government may plan and implement strategies to avoid, mitigate, or prevent undesirable impacts based on both real-time observations and contextual analysis of the environment.

An urban sensing network application for environmental monitoring is presented here. In contrast to earlier event-driven data gathering, this application supports periodic data gathering, along with data analysis and trend identification. This research includes real-time support for visual presentation of sensor node reporting in a geographical and temporal context, suitable for representation, spatial analysis, and interactive visualization in a geographic information system (GIS). The coupling of GIS presentation with wireless sensor network has been investigated for vehicle-related air pollution monitoring (Cordova-Lopez et al. 2007) and fire rescue applications (Sha et al. 2006). Previous research, however, has been limited to solely presenting the sensed records with a GIS and does not involve spatial analysis and data mining to identify patterns and establish relationships to support decision making.

The overall goal of this software is the implementation of web-based monitoring and prediction processes built upon the wireless network sensor (WiNS) architecture (Morreale 2008; Morreale and Suleski 2009). This software is able to monitor and check incoming sensor data against an existing database and produce charts predicting the sensors' next probable reading.

The scope of this software (Suleski 2009) extends the robustness of the current WiNS architecture to implement a system from which administrators and other researchers are able to generate real-time alarms from incoming sensor data, and also allow the implementation of a prediction based chart generation page, to display possible future readings. By implementing a system which can monitor and distinguish between normal sensor variations and underlying patterns, to generate real-time alarms, researchers can be instantly notified the moment a pattern or event is discovered. This is most important for the early warning of natural disasters, such as hurricane Katrina (2005) or manmade disasters such as the coal ash spill in Tennessee (2008).

2 Wireless Sensor Network Design

2.1 Network Topology

The initial network topology (Figure 1) is that of a deployed three tier network, consisting of a Mote Tier, Server Tier, and Client Tier. The Mote Tier deals with the wireless mesh network of sensors. This mesh network allows for network connections to be seamlessly rerouted around dead nodes and new nodes to be added with ease. The Server Tier includes the database and logger, while the Client Tier deals with visualization and analysis tools.

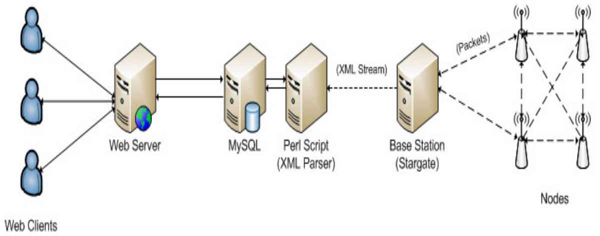

Figure 1. Network Infrastructure Diagram

By default, once the base station receives the packets from the nodes, the received data is archived into a local SQLite database on the base station. The problem with this design is that it did not allow for Server and Client expandability. SQLite is not a client/server database, and as such, external resources are unable to retrieve the sensor data. In addition to the default infrastructure developed by Crossbow for network deployment, additional Server and Client tier applications were designed and implemented.

2.2 WiNS Architecture and Component Design

At regular intervals, of approximately 3.5 minutes, the deployed wireless nodes wake from their sleep, sample the onboard sensors, and send update packets to the base station, via a mesh network. The packets are received by the base station, decoded and archived into a local SQLite database within the base station.

The base station receives the incoming packets on a separate Linux server, running a MySQL database, installed in the Server Tier. Clients are able to establish a socket connection to the base station, and receive an XML Stream of all incoming packets. An XML Parser Perl script was developed to be run on the Linux server.

This script creates and maintains a constant socket connection with the base station, receiving a steady stream of sensor packets. As each packet is received, it is analyzed to determine if it is carrying data relating to the readings of the onboard environmental sensors, the only packets vital to conduct this research. Packets flagged containing this data are then parsed and the environmental readings are inserted into the MySQL database, un-flagged packets are discarded. From this point, the sensor data is accessible by external resources.

A web-based user interface was developed and installed in the Client Tier. The interface is used as a front-end to the MySQL database; allowing users to see a visual representation of the sensor data based on criteria supplied by the user.

Expanding upon the WiNS architecture, additional modules were developed and implemented. Figure 2 illustrates the final architecture design, reading from right to left. Wireless nodes take sensor readings and send packets back to the base station, which then archives them into a local SQLite database, as well as sends them out in an XML stream via a socket connection to the *XML Parser Module*. The *XML Parser Module* parses the packets to retrieve vital sensor readings, which are then passed to the *Alarm Monitor Module.* The readings are also printed to the *Admin Monitoring Module* as they are received. The *Alarm Monitor Module* then compares all un-tripped alarm events pertaining to node id, from which these readings were sent from, to the current sensor reading values. If it is determined that an alarm has been raised the *Alarm Monitor Module* calls the *Alert Emailer* which then sends an alert out to the appropriate party. The *Alarm Monitor Module* then updates the database assigning a 'tripped' value to the alarm event, removing it from future checks until it has been reset from the *Alarm Website*. The sensor readings are then archived into the MySQL database.

Since sensors readings are not received at exactly the same time every hour, an *Average-R Module* runs every fifteen minutes, averaging the last fifteen minutes of readings into one value, allowing other modules to accurately combine multiple node readings.

The *Predictor Module* is run every fifteen minutes, calculating future probable sensor readings. Once the *Predictor Module* has completed, a *Chart Generator Module* is called to produce the prediction charts displayed on the *Prediction Website*.

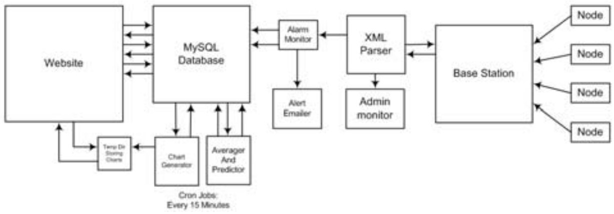

Figure 2. Architecture Diagram

2.3 Green Wireless Sensor Network Architecture

The WSN architecture is considered green for the following reasons:

1 Periodic data reporting, with the periods set by the users, permits less energy use overall and avoids energy spikes, such as those which are commonly found with event-driven data reporting. For example, in the presence of an event, sensors utilized large amount of energy often reporting redundantly. In contrast, the GWSN outlined here supports periodic reporting and a corresponding amount of energy is saved, depending on the period used, but by having a dynamic, user-specified periodic reporting rate, overall energy consumption is reduced a variable amount.

2 Absence of timestamp synchronization permits the sensors to be considered autonomous systems. As a result, there is no need for blast communications to all sensors to synchronize them and the returning responses from each sensor, with the resulting REQ/RESP pairs until the SYN process has completed. Depending on the frequency of reporting, and the energy consumption of the sensors, this can result in a savings of up to 50% of the network energy usage, which can be used to report sensor reading, rather than expending energy on the management of a central synchronized clock.

3 Implementation and operation

3.1 Prediction Algorithm

During development, the prediction model module was designed to predict the next future reading that was to be received by the base station. The initial algorithm used was of a percent deviation, due to its simplicity. The previous reading and the most current reading are compared and the percentage difference, if any, is determined. The calculated difference is then applied to the current reading, with the resulting value used as the prediction of the next reading.

There are other possible algorithms which can be used instead of a simple percent deviation calculation such as an adaptation of the Least-Mean-Square algorithm, which is aimed at data-reduction transmissions in wireless sensor networks (Santini and Rőmer 2006). The Levenberg–Marquardt algorithm is another possibility, popularly used as a curve-fitting algorithm used in many software applications for solving generic curve-fitting problems.

3.2 WiNS Network Operation

Using a wireless sensor network (Morreale 2008; Morreale et al. 2009), a large dataset of environmental data had been gathered over a series of months. The WiNS software provided support for real-time data presentation on the web (Figures 3 and 4).

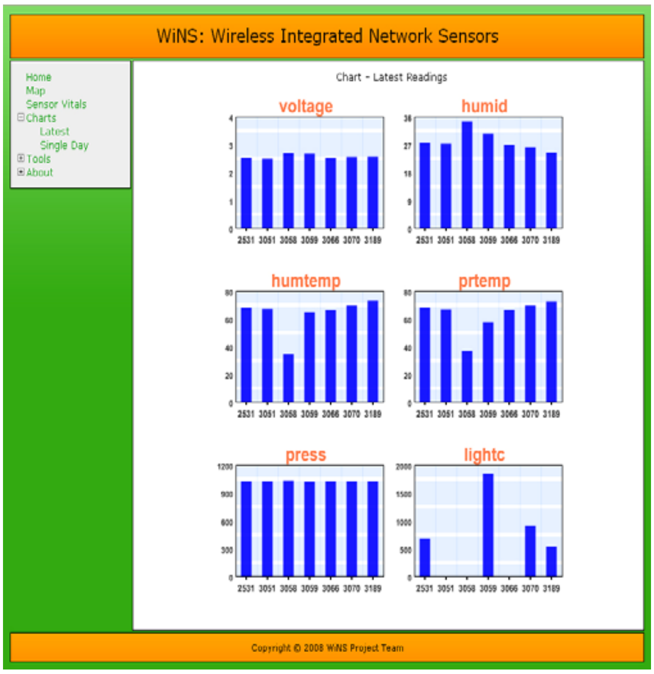

Figure 3. WiNS Bar Chart Display of Real-time Sensor Data

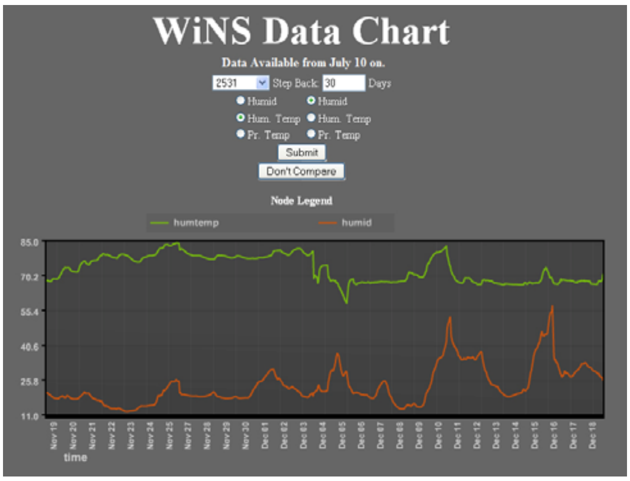

Figure 4. Prototype screen shot from WiNS application, with sensors correlated by data and time.

The wireless sensor network had been established using Crossbow sensors, a commercially available system. The sensors report their readings in real-time to a MySQL database server. The Crossbow sensors would report the following environmental readings: Humidity, Humidity Temperature, Pressure Temperature, Pressure, and Light Concentration. The pressure and humidity temperature stems from the pressure and humidity chip within the sensor node. The Crossbow sensors nodes have collected over 1.5 million rows of environmental readings over the time period the WiNS network has been in operation. The collection of these readings is on-going at regular intervals, reporting to the MySQL database server.

In sensor networks, due to the overwhelmingly large volume of data which can be reported, parameters are used to adjust the frequency and size of data reports. In preparing data in a chart or graph format for visual presentation and understanding, the timestamps on the data gathered are important for data understanding and provided the most significant design challenge. Data validation and accuracy assurance is also a concern.

3.3 Timestamp Reconciliation

In earlier systems, such as an event-driven volcanic monitoring system (Werner-Allen et al. 2006), reported data was required to be accurately time-stamped for scientific use and the timestamps were synchronized by using a global clock. By using the Flooding Time Synchronization Protocol [FTSP] to share a global time with the wireless mesh network used for reporting volcanic events, the data would arrive from the sensors with appropriate timestamps. However, on occasion, FTSP would fail, resulting in unusable data for that application. In contrast to an event-driven global time system, the wireless sensors used here were not universally synchronized on a regular basis. Additionally, the WiNS sensors were not reporting on an event-driven basis, but reported instead at *periodic* intervals, over time.

For example, although the sensor nodes were reporting to the database every three minutes, the timestamps entered into the database weren't precise, so that it was difficult to line up the readings on the charts appropriately. One node might have a time stamp of 14:53:44, while a second node might have a time stamp of 14:52:58. This would be considered normal, as each wireless sensor is an independent system and may have its own internal 'clock', but at the centralized database, this time discrepancy presented significant problems when trying to display multiple nodes on the same chart.

In order to identify and overcome this data reporting challenge, a Perl script was developed and, initially, run at midnight every date. The goal of this script was to sort the received data in sequence by node so that each reading would line up at specific time intervals, selected to be 15 minute windows. This window selection parameter was in part based on the stability of the data being using for this development. More volatile systems might use shorter windows while even more stable systems might select longer windows. The absence of a global clock has been shown to preserve timing accuracy, while permitting the network operation to continue for months without failure, while preserving timing accuracy for 99% of the collected measurements (Gupchup et al., 2010).

3.4 Data Validity Assurance

Data validity was preserved by not altering the original dataset in any way. Rather, the data was inserted into a newly developed dataset, which was then used to develop the charts for presentation. The entire GUI was developed around the needs of the user.

This approach of preserving the original dataset, while making a copy, and adjusting the dataset copy to support a universal timing for data correlation and web presentation is a unique approach for sensor data. Real-time systems often have timing correlation issues, but the approach used here is innovative as it is preparing the data for interpretation and presentation on the web, while preserving the independence of each sensor node.

Later, a further refinement was added to the system. Initially, all data from the prior 24 hours was selected and sorted by 15 minute intervals per node. This resulted in a long script of frequently redundant data values. As an improvement, the script was modified to run every 15 minutes and average all data from the prior 15 minutes into one reading, which was inserted once. By breaking the 24-hour task into numerous smaller tasks executed at 15-minute intervals, the accuracy of the data remained assured, with data validity high.

All incoming data must be tested for validity. At present, there is no inline data sink to filter erroneous data. Instead, data is validated after is it gathered, by an independent script. With the current architecture, it would be easy to insert an outlier detection mechanism as part of the alarm monitor module or xml parser module.

4 Green applications of the Wireless Sensor Network

We report here on three ongoing efforts to use the wireless sensor network tool for environmental applications in an urban environment.

4.1 Micro-climate monitoring in an urban campus environment

The first application intends to use monitoring sensors to collect information regarding spatial variation of the microclimate in an urban campus and the temporal patterns of such spatial conditions. In a full-blown system that runs over a particular period of time (a few months or years, for example), the spatiotemporal sensing data could be analyzed with a GIS or through data mining to extract the daily and seasonal cycles of microclimate parameters. Such parameters will be correlated with campus topology and land cover to establish relationships. The relationships could be used for many green management strategies such as targeted and varied-timing of lawn watering based on temperature and moisture conditions, adaptive tree planting for shading of overheated buildings and spaces.

Current focus is real-time temperature monitoring of campus office spaces. According to the US Department of Energy, HVAC (heating, ventilating, and air conditioning) accounts for 40 to 60 percent of the energy used in U.S. commercial and residential buildings. This represents an opportunity for significant energy savings through close monitoring of indoor temperatures and control of the HVAC settings. There has been a common non-environmental considerate practice in the US that commercial (office) buildings tend to be over-cooled in the summer (< 20°C) and over-heated in the winter (>20°C). For less attentively managed buildings, temperatures could be even more anti-nature or environment. A temperature sensing network in such office buildings (especially in industrial complexes or on campuses where a large number of buildings are under concern) and the real-time information provided through an appropriate visual interface provides planners with an effective tool to monitor and control excessive heating and cooling situations and thus save significant amounts of energy. Figure 5 illustrates a visual interface for such a sensing network application.

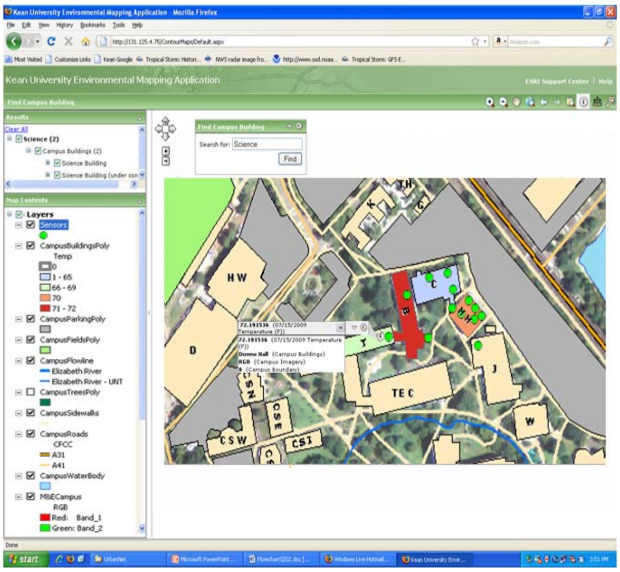

Figure 5. Visual interface of building temperature sensing

Once data over a period of time is collected, spatiotemporal patterns of microclimates inside campus buildings will be presented in a visual form using both a GIS and animation. These visualization tools help to promote awareness to the campus community and provide guidance to facility management and operations.

4.2 Air quality monitoring and traffic control in an urban community

The second application intends to address one of the most common human-environment interactions in an urban community—traffic related air condition dynamics. In the planned system, atmospheric conditions such as temperature and gas concentrations including CO, CO_2, etc. will be collected using the sensor network. Traffic count data will be obtained either through sensors or distributed reports from participants with wireless devices (smart phones, for example). Air currents over campus will be calculated from wind data. Air quality, traffic volume, and meteorological measures will be correlated and relationships be extracted through data mining. For a simple scenario, if CO_2, CO data exceeds a certain threshold, given the external temperatures (as CO_2 and CO measurements are affected by the air temperatures), traffic count will be examined. If CO_2, CO, and traffic count have all increased, a predictive model established through data mining will be used to determine other areas in the same traffic flow pattern that may be experiencing poor air quality due to increased traffic. Alerts can be provided to traffic authorities, and traffic could be re-routed to less congested roads. In a more complex application, better traffic pattern, parking design, or class scheduling strategies on a commuting campus could be suggested based on long term monitoring and modeling results.

A proof-of-concept system is currently under development around the Kean University campus community. The campus is located in the city of Union, New Jersey, which is in the New York Metropolitan area (Figure 6).

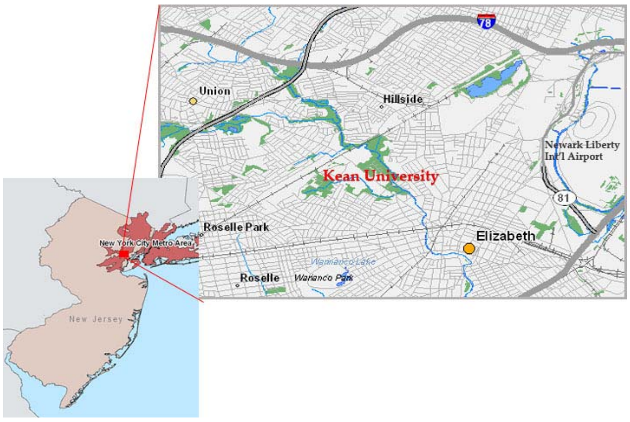

Figure 6. Kean University Location

Union County is the most densely populated county in the state with 5,000 people per square mile and is near Newark Liberty International Airport (Figure. 6).The campus lies within an urbanized region, typical of the area, but consists of a variety of landscape characteristics to be representative of multiple scenarios. The university is a commuter college with majority of its students commute by cars. Traffic volume could be extremely high during common class hours and parking has been a serious problem on campus. The current prototype system integrates GIS mapping with sensor network data to monitor air quality around campus. Only a limited number of nodes are established on major pivot points in and around campus to initialize the effort. Spatial interpolation is conducted with GIS to generate areal coverage of air quality distributions over the entire study area for contextual analysis.

A high resolution NAIP real color orthoimagery of Union County served as a base for the spatial-visual framework in which layers of campus buildings, trees, lawns, stadiums, sidewalks, and other features were digitized based on the orthoimagery. Layers such as flow lines, water bodies and roads were obtained from New Jersey Department of Environmental Protection while landmarks, schools, and other human features were extracted from the ESRI GIS Data archives online (www.esri.com/index.html). Demographic data was extracted from 2002 census. The steps of clipping, digitizing, georeferencing, rectification, overlay, classification, map design, online map publishing, spatial interpolation, and data mining were used to create the root database for the project. This provided information about the study region's detailed spatial mosaic of a variety of physical and human landscape. Similar procedure and protocol would be followed to scale up the system by covering broader regions.

An online mapping site was established to provide public access to the base layers as well as environmental monitoring results, as would be expected in real-time applications for practical use, and in order to provide an operational template for the manner in which data and analyses would be displayed by user communities in the decision-making process. The site allows user-guided inquiry and query (Figure 7).

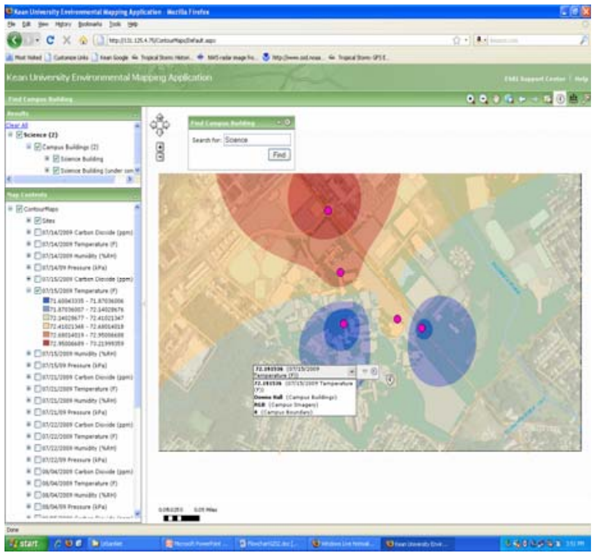

Figure 7. Interactive web-mapping site

Animated visualization of monitored environmental variables was also created to display dynamics of changes for interpretation of relationships and temporal patterns. The intent is for a user to manipulate the current data with regard to background or baseline information so as to determine an appropriate course of action, if any, is or will be needed in the local area (Figure 8).

Figure 8. Interactive and animated visualization

4.3 Integration of sensor data for sustainability

In the identified system, further development is providing more air quality measures for collection and correlation with meteorological and traffic conditions. Spatial interpolation will indicate areas of decreasing air quality and increasing traffic in near real-time as snap shots. Long term temporal trends, daily, weekly, and seasonal patterns will be revealed through animated online maps.
Data mining results will also be visualized through interactive online maps, with which hazardous conditions can be predicted over time, and avoided. Traffic control such as rerouting, campus parking lot closure opening schedules will be made more informative given the available system-wide information. This is in the broader context of sustainable urban environment planning or climate change evaluation and response.

5 Conclusions and Future Work

Overall performance of the implementation of the predictive model has been positive. Predictions are accurate to a varying degree, barring any sudden environmental shift.

Contributions of this approach include:

periodic data collection and reporting, in contrast to sensor systems which support event-driven data collection and

timestamp reconciliation, where each sensor is treated as an independent system. Timestamps are sorted in order of receipt from the reporting sensor, rather than trying to implement and maintain a global time clock across the system. This approach dynamically supports an increasing or decreasing sensor population reporting over time, which is highly likely in future systems or mesh networks.

A shortcoming of the current algorithmic implementation is the inability to predict future readings, past the next upcoming reading. Purposed future expansion of this module is to include the functionality to predict readings for *any* date and time, most likely using the Levenberg-Marquardt algorithm.

The portability and flexibility of this system is also being enhanced. For utility with a full range of applications, a green wireless, light-weight, flexible system such as that outlined here is ideal.

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