REAL-TIME PLUME DETECTION IN URBAN ZONES USING NETWORKED SENSING

Tracy Kijewski-Correa, Jeffrey Talley
Department of Civil Engineering and Geological Sciences, University of Notre Dame
156 Fitzpatrick Hall
Notre Dame, IN 46556 USA

Peter Bauer, Martin Haenggi, Panos Antsaklis, Michael Lemmon, J. Nicholas Laneman
Department of Electrical Engineering, University of Notre Dame
275 Fitzpatrick Hall
Notre Dame, IN 46556 USA

Luis Montestruque
EmNet LLC
12441 Beckley St.
Granger, IN 46530 USA

Jack Fulton
Naval Surface Warfare Center, Crane Division
300 Hightway 361
Crane, IN 47522-5001 USA

Gopal Patnaik
Laboratory for Computational Physics
Naval Research Laboratory, Code 6410
Washington DC 20375-5344 USA

ABSTRACT

The release of a chemical/biological/nuclear (C/B/N) agent in a city remains a viable threat. As these silent, invisible and odorless plumes can cause massive casualties that would overwhelm emergency facilities, modeling, tracking and real-time prediction of plume dispersion and lethality is central to developing a user-friendly first responder's tool for evacuating civilians and managing emergency personnel. In response to this need, the authors propose a fusion of plume detection by embedded wireless sensor networks, of both meteorological and chemical sensors, with a plume-prediction model called CT-Analyst to hindcast plume origins and project subsequent dispersion in near real-time. This paper overviews the network and algorithm development, the demonstration to be conducted on the campus of the University of Notre Dame, and the extensions of these concepts to other biological hazards such as E.Coli contaminations in drinking water supplies.

INTRODUCTION

One of the nation's greatest fears is the intentional or accidental large-scale release of a chemical/biological/nuclear (C/B/N) agent in a densely populated area. The silent, invisible and odorless plume could cause massive casualties that would overwhelm emergency facilities. As such, modeling, tracking and real-time prediction of plume dispersion and lethality is central to Homeland Security in developing a user-friendly first responder's tool for evacuating civilians and managing emergency personnel.

Tracking of plume evolution can be accomplished through one of two mechanisms:

1) Physical detection of the plume by embedded sensor networks.
2) Prediction of plume dispersion by computational models.

The former approach provides actual measurements of the plume boundary, though it is limited by sensor sensitivity and cost and lacks the ability to predict plume trajectories. The latter approach, which has received more attention within the Homeland Security community, is completely reliant on the accuracy of building-resolving Computational Fluid Dynamic (CFD) models that have yet to be comprehensively validated in dense urban zones representative of the highest value targets. Computational models such as FAST3D-CT, a Large Eddy Simulation (LES) package developed by the Laboratory for Computational Physics and Fluid Dynamics at the Naval Research Laboratory (NRL) [1], implicitly model unique urban features such as large scale vortex shedding from buildings, convective heating, complex flow patterns in urban canyons and recirculation zones that trap contaminants, dramatically increasing the local concentration of toxic agents as plumes take on rather unexpected paths [2]. Unfortunately, these models require immense computational resources and are thus not extendable to a real-time framework to serve the needs of first responders.

A computational compromise is reached by alternative dispersion models, e.g., Gaussian puff models like DTRA's SCIPUFF [3]. Unfortunately, such models average out all turbulent characteristics of the wind field and ensuing plume, losing any evidence of high concentration zones where plume density can be six times the average, yielding an unrealistic picture of the safe lateral boundaries of a C/B/N plume [4]. Furthermore, discrepancies between Gaussian puff models and high resolution CFD models are more pronounced in denser, taller and highly corrugated urban landscapes [5]. Thus, in order to maintain accuracy while minimizing computational burden, a real-time software called CT-Analyst was recently introduced, which conservatively predicts the hazard area based on multiple pre-computed realizations from FAST3D-CT condensed into dispersion nomographs [6]. Fully-functional versions of this software have already been developed for a number of urban zones, including Chicago and Washington DC.

Despite the availability of software such as CT-Analyst, the prediction of plume evolution in "cities with high profile morphology and a great deal of variation produce hazard areas whose characteristics are quite sensitive to release location and meteorological conditions" [5]. As such, models like FAST3D-CT and even CT-Analyst are "…no more accurate than the wind morphology forecasts…" feeding into them [6]. In most cases, such meteorological data is reported at nearby airports and deviates considerably from the actual conditions in the downtown area, due to the significant spatial variability of the wind field in urban zones. Thus, despite all the computational advances of LES, their forecasts are still limited by the uncertainty of data input into the model.

Initially, CT-Analyst was developed with the expectation that basic meteorological data and evidence of plume location would be input manually as anecdotal data on the event becomes available. This information would then enable not only the source of the attack to be hindcast, but would also enable the forward projection of the plume to be simulated. Unfortunately, this information many not be immediately available, particularly in any quantitative form, thus hindering the utility of this first-responders tool. Reliance on accurate data to drive these models subsequently motivated the current research program: automated interfacing between CT-Analyst and distributed networks of meteorological and chemical sensors capable of providing continuous, quantitative evidence of plume migration and environmental conditions supporting its dispersion. This data fusion is achieved through embedded wireless sensor networks.

In this so-called hybrid framework, the CT-Analyst model will offset the limits in practical density of a stand-alone sensor network for plume detection, while the real-time sensor data will feed the predictive model for more accurate delineation of plume boundaries and release points. The proposed network will provide point verifications of plume location as well as accurate real-time meteorological data at various locations in the an urban zone using stationary nodes of low-cost sensors, as well as mobile sensing capable of moving more expensive but sensitive instrumentation along plume boundaries. Such an approach is in direct response to a recent NRC report [7] calling for a "…more [effective means to] assimilate into models an appropriate range of meteorological data from observing systems as well as real-time data from C/B/N sensors… "

Thus, the objective of this research program is the development of the embedded sensor network and its interfacing with CT-Analyst, including appropriate algorithms for in-network data processing, whose proof-of-concept will be demonstrated through a controlled small-scale release of a benign chemical agent, sulfur hexafluoride (SF6), on the campus of the University of Notre Dame in the fall of 2008 followed by a larger-scale deployment and release in a dense urban zone the following year. This paper discusses the development of the network as well as the demonstrations that have been conducted to date.

FIGURE 1. InfraRan specific vapor analyzer (left) and WTX510 meteorological sensor wired to I-Node platform.

HARDWARE

EmNet, LLC provides the wireless sensor network (WiSN) hardware enabling real-time monitoring of the environment. The WiSN is composed of three distinct types of nodes, which have been extensively field tested as part of a urban deployment in South Bend, IN, to monitor Combined Sewer Overflow (CSO) Events [8]. Instrumentation nodes, or "I-nodes," collect data from the environment and transmit it wirelessly to the nearest Gateway node, or "G-node." The G-node collects the data from the surrounding clusters of I-nodes and uploads it to a password protected web portal, where the raw data is processed and displayed, via a secure internet connection. If the distance between the I-node and the G-node is too great, a Repeater node, or "R-node" can be added, providing a bridge between the two nodes. In this way, the WiSN can monitor large areas of interest in real time. Furthermore, the use of clusters of sensors enables a scalable architecture that permits the WiSN to be applied readily to small demonstration areas, like that at the University of Notre Dame, or large deployments in major cities. I-nodes can be used as stationary sensor platforms, distributed over an area of interest, or can be affixed to a mobile platform (robot), as discussed in the following section.

The I-node platform is robust enough to accommodate a wide variety of sensors, providing local memory and processing capabilities for basic data acquisition and communication by wireless radio. For the present study, this platform interfaces the InfraRan Specific Vapor Analyzer by Wilks Enterprise, Inc., a infrared-instrument for the detection and measurement of contaminants in ambient air at parts per million (ppm) levels (Fig. 1). This instrument will serve as the chemical detector in the WiSN for the purposes of demonstration and has been able to detect SF6 down to a concentration of 20 ppb (parts per billion) in bench-testing. Environmental conditions regulating plume dispersion will be monitored by the Vaisala WXT 510 Meteorological Station with ultrasonic wind velocity measurement, as well relative humidity, barometric pressure and temperature (Fig. 1).

MOBILITY

The mobile component of the wireless sensor network is comprised of a robot that carries a sensor suite tailored to the detection task at hand. Originally, a Pioneer AT-4 was selected, but later was exchanged for a 2-wheel Segway research platform for reasons of reliability. The task of the robotic platform is to take sensor readings in an open outdoor area that provides connectivity to the stationary WiSN. A initial proof-of-concept was conducted for the robot over an artificially restricted the area of 40 m x 50 m. The readings from the mobile I-nodes were transmitted to the G-nodes throughout the demonstration. Based on the sensor readings, the robot can then either work off its pre-programmed sequence of waypoints or if needed, an ad-hoc waypoint could be specified. This way, the mobile robotic platform complements the stationary WiSN and takes readings in areas of high uncertainty, which can be caused by a variety of factors such as faulty sensors, large distance between sensors, calibration problems, high risk areas, etc.

FIGURE 2. Segway mobile platform.

The Segway platform used in the mobility proof-of-concept was equipped with a 2-D laser range finder for obstacle avoidance and a GPS system for navigation and guidance. It also carried an I-node measuring air-temperature rather than SF6 concentration, simply because the Wilks sensors were still being fabricated at the time the mobility component was being tested. Still, the platform allows for a large payload and could even accommodate large and heavy sensors weighing up to 50kg.

Initial proof-of-concept for the mobile component consisted of a patrolling task where the robot had to visit certain pre-specified waypoints. The robot repeated its trajectory several times until dynamically a new waypoint was added. Following the addition of the waypoint, the robot explored the area around this new waypoint location and took measurements there. Battery power was sufficient to operate the platform for several hours. In addition, there is the option of powering external devices. The experiment also showed that wireless node placement is critical on the robot due possible interference with the GPS signal. This effect was especially pronounced near large buildings and was remedied through shielding. The mobile platform proof-of-concept can be viewed at: http://www.nd.edu/~moses/videos/vex/SegWay_Task1_v2.wmv.

WIRELESS COMMUNICATIONS

Resource- and time-efficient delivery of sensed data is a prerequisite for the successful operation of a WiSN used for detection and tracking. Thus the development of network hardware, architectures, and protocols that guarantee reliable communication over multiple hops (links) under delay-constraints is a pre-requisite for the present application, using an interdisciplinary approach based on information theory, control theory, and networking.

The plume tracking application and its heterogeneous network architecture provide opportunities for advancing research in low-cost embedded radio networks for defense applications, including designing adaptive radio modules and developing optimized cross-layer protocols. Most sensor network and node technologies have been developed with static nodes in mind [9]. The combination of static and mobile sensing I-nodes, as described in the previous sections, motivates a re-examination of the radios used for communication. A *software-defined radio (SDR) architecture* provides the necessary flexibility and radio adaptability at reasonable cost. Having a single transceiver architecture that adapts to various configurations (namely, static-static, static-mobile, and mobile-mobile) aids in network middleware development if the right abstraction barriers are designed into the network protocol stack. The present implementation is based on the GNUradio platform [10].

In an interference-limited scenario, such as during this project's demonstrations on a university campus or city center, requires radio adaptability to ensure robust network operation. Thus software radio-based repeaters are also used in the study, where SDR nodes assist conventional R-nodes with their transmissions if needed to enhance the connectivity of the network.

Furthermore, in the case of real-time plume detection, the deployed wireless communication network is required to transmit information to both the G-nodes and mobile I-nodes under strict time and reliability constraints. Therefore, routing protocols appropriate for critical applications that involve control actions must be developed. In the present application, mobile units need to be guided to regions where the detection and tracking application would most benefit; therefore, these algorithms need to guarantee upper bounds on the delays and be adaptive to changing conditions in the network by selecting alternative routes on-the-fly [11]. In the present application, mobility increases the difficulty of dependable routing due to channel fading and changes in the network topology and connectivity, which results in unreliable links, link breaks, and additional control traffic needed to keep track of the mobile units' locations. As a result, various control algorithms that perform well in such adverse environments, where the wireless channel causes packet loss and unknown delays, have been introduced [12, 13]. Finally, the network lifetime needs to be

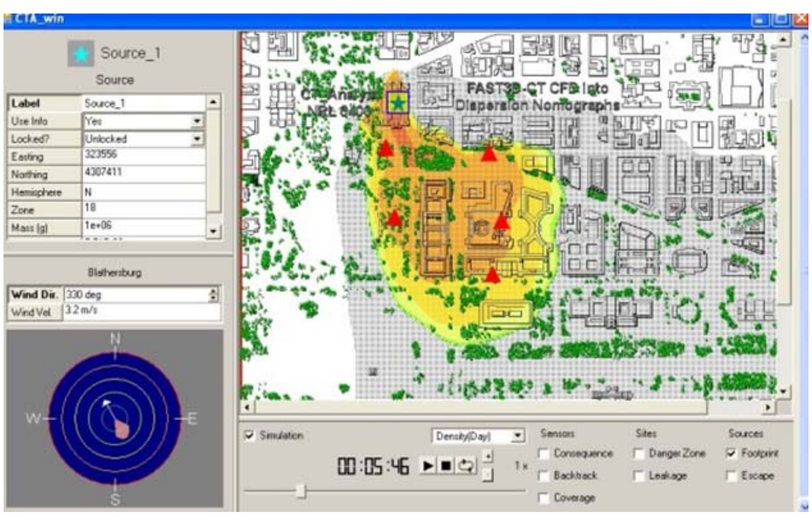

FIGURE 3. Screen shot of CT-Analyst user interface.

maximized; this is achieved by load balancing, which is particularly critical in the critical zone near the G-node. This zone contains the few I-nodes that are able to connect to the G-node and therefore have to carry all the relaying burden.

INFORMATION PROCESSING

The distributed InfraRan sensors deployed throughout the demonstration area collect concentration values of the sensed agent, while meteorological stations provide data on local atmospheric conditions. These outputs from the WiSN are introduced as variables in CT-Analyst, providing a real-time automated input to drive the computational model, whose user interface is shown in Figure 3. This is conceptually shown as the Sensing Stage in Figure 4. CT-Analyst then generates a data set of simulated concentrations, as a function of a series of "best guesses" for the release point of the airborne agent, from fixed sensor points in the detection zone. These simulated concentrations are then compared with actual sensor concentrations taken from the InfraRan detectors in the WiSN. An optimization tool correlates the simulated and collected concentration data sets to determine the most likely source of the contaminant, completing the Hindcast and Optimization Stages in Figure 4. Once determined, the subsequent dispersion of the plume can be simulated by CT-Analyst. This entire process takes a matter of seconds. The recorded concentrations can additionally be used to refine the plume trajectory forecast by CT-Analyst, as shown in Figure 4, as part of the Refinement Stage. The optimization hindcasting algorithm has been validated using a number of blind release scenarios, proving that source locations can be determined with errors less than 18 meters and release times within 6 seconds.

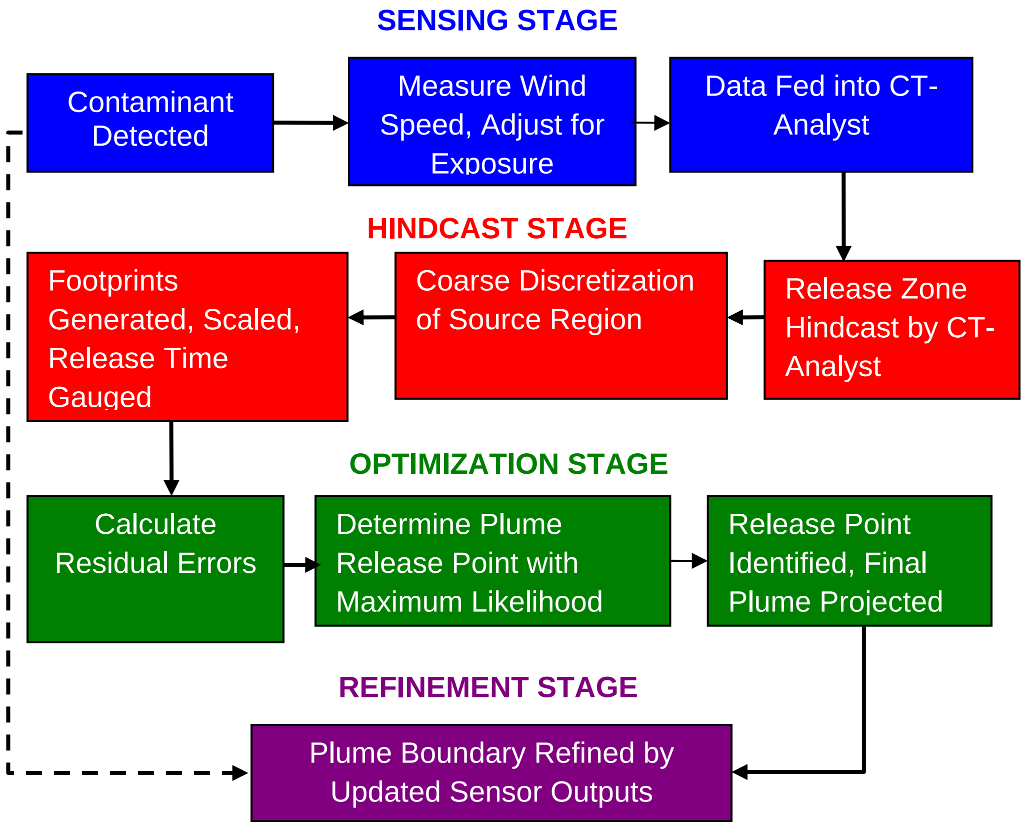

FIGURE 4. Flow of operations in multi-stage hybrid detection scheme.

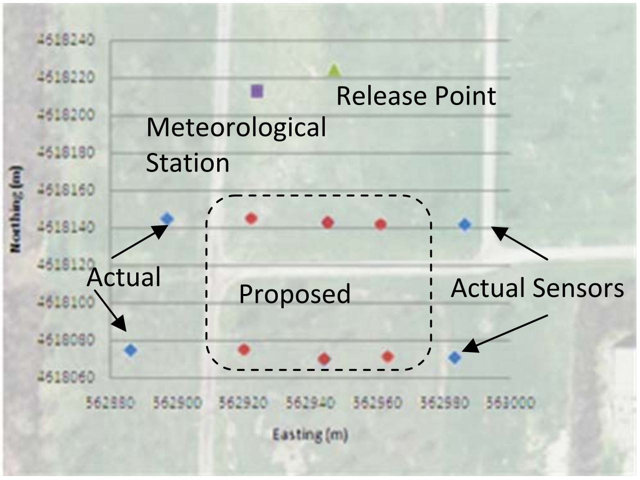

FIGURE 5. White Field deployment.

DESIGN OF RELEASE PROTOCOL

In preparation for the small-scale demonstration on the campus of the University of Notre Dame in the Fall of 2008, a series of SF6 releases were conducted to establish requisite wind conditions for adequate dispersion, release rates, and the spatial distribution of the InfraRan sensors. Due to the aforementioned detection capability of the InfraRan sensor, release protocols for SF6 must achieve concentrations of 20 ppb or higher, as confirmed using bag samplers. This is significantly higher than prior full-scale plume tracer studies, which primarily used bag samplers and off-line, laboratory analyses to determine concentrations and not fast samplers like the InfraRan.

The first SF6 release in the protocol development stage was conducted on the morning of August 24th 2008 in White Field, just north of the University of Notre Dame main campus. Initially two arcs of sensors were to be placed at distances of 75 m and 150 m from the release point, with sensors 20 m from the centerline on either side. During testing, the wind direction was observed to oscillate significantly, requiring the sensors to be dispersed 45 m to either side of the source, as shown in Figure 5.

Bag samplers were filled at 5 minute intervals throughout the 20 minute SF6 release period. These samples were then analyzed off-line to determine the tracer gas concentration. The rate of emission of the SF6 gas was also varied between 25 L/min and 100 L/min with no noticeable

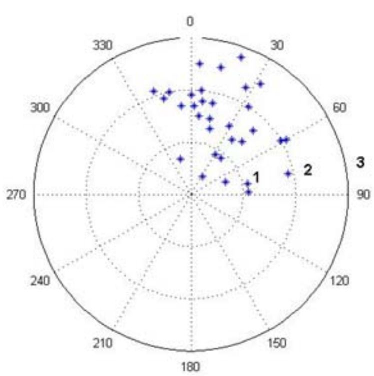

FIGURE 5. Wind speed (m/s) and direction data from White Field test.

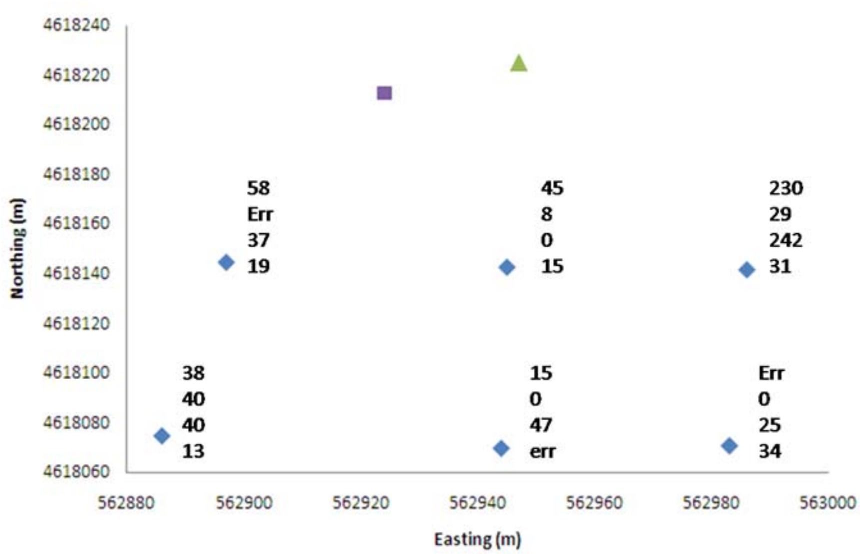

FIGURE 6. SF6 concentrations from White Field test (ppb) with concentrations at 5, 10, 15 and 20 mins (top to bottom) at each location.

effect on the downstream concentrations. The wind direction remained fairly consistent (N to NE) during the testing period, with an average wind speed of 1.7 m/s (Fig. 6). While the average wind speed was lower than most previous tracer studies, it did not have an adverse effect on this test. The peak concentration values recorded were above 200 ppb, but the bulk of the data points resided between 10 and 50 ppb, as demonstrated by Figure 7, showing each of the SF6 concentrations recorded at the four time intervals. The test confirmed the existing testing protocol is sufficient to generate downwind concentrations at and above the lower detection limit of the InfraRan sensor. This protocol will be used in the Fall 2008 demonstration on the South Quad of the University of Notre Dame using five InfraRan stationary I-Nodes, flanked by bag samplers for sensor validation, and 5 perimeter meteorological I-Nodes to demonstrate the performance of this WiSN to detect SF6 plume dispersion in built up areas.

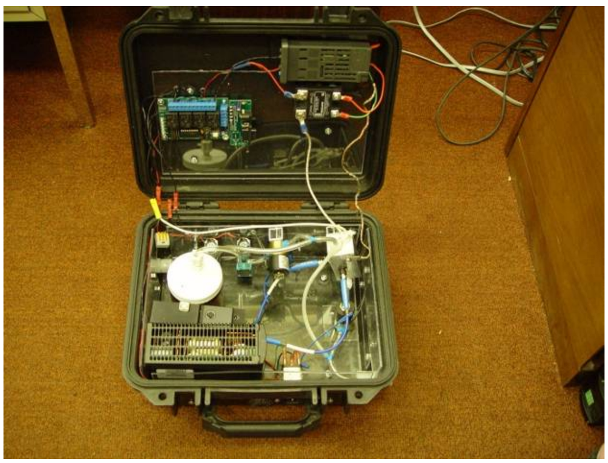

FIGURE 7. Photo of prototype E.Coli sensor.

EXTENSIONS

The WiSN concepts developed by this research are simultaneously being extended to the examination of water quality to protect against the deliberate release of harmful agents, like *Escherichia* coli (E.Coli), into drinking or recreational waters. As the concentration of E.Coli can vary in relation to environmental conditions, time of day and location a point sampled, the common use of 24-hour assay is poor indicator of current water quality [14]. Recognizing this, this project is developing networks of rapid sensors capable of in-situ monitoring of pathogens in recreational and source water. The focal point of these efforts is an optical sensor for the in-situ detection of E.Coli, shown in its current prototype form in Figure 7. The sensor monitors increases in fluorescent intensity as a measure of E.Coli concentration.

From July 22-30, 2008, the performance of this prototype was demonstrated the use of an optical sensor for the detection of E.Coli in Balbriggan Harbor, County Dublin, Ireland. The demonstration consisted of two prototype sensors providing continuous monitoring of E.Coli levels and was supported by manually drawn samples enumerated using approved culture methods. The deployment at Balbriggan Harbor produced 25 individual sampling events by the sensor prototypes. The sensors were set to draw and assay samples every 8 hours. Despite the relatively low E.Coli concentrations, the average time to detection, determined as a fluorescent intensity of 1.25 x the background noise, was 0.99 hrs. This is approximately 5 hours earlier than the times of detection obtained from similar E.Coli concentrations in fresh water.

CONCLUSIONS

The integration of wireless sensor networks with computationally efficient software for plume dispersion and hindcasting, provides an effective and economical platform for real-time decision making in the event of a chemical, biological or nuclear attack in an urban zone. This study overviewed the development of wireless sensor hardware, communications and information processing to enable a system of stationary and mobile chemical detectors to feed real-time concentration data into a computational model for rapid determination of threats to urban areas, in both air and water. Preliminary proof-of-concept has established the viability of the approach and further small-scale field testing will be conducted on the campus of the University of Notre Dame in the Fall of 2008, followed by larger scale testing in a municipal area the following year. This system has the potential to rapidly provide critical information to aid in the evacuation of areas using plume predictions derived from real-time in-situ observations in a distributed wireless sensor network. As the system features user-friendly graphical user interfaces and is web-accessible, it can be easily used by first responders in the field for the protection of human life.

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