A system to provide real-time collaborative situational awareness by Web enabling a distributed sensor network

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ABSTRACT

The paper presents two systems called PATS and SAP that when integrated realize Sensor Web Enablement (SWE) of spatially distributed mobile sensors. The Personal Alert and Tracking System (PATS) consists of a networked collection of custom-designed low-power wireless nodes, arranged in ad-hoc network topologies, to provide tracking for wild land firefighters. These mobile nodes form arbitrary network topologies and use a multi-hop packet routing protocol to relay sensor data to the command center. The multi-hop capability enables robust communication in a variety of environments by routing around natural and man-made terrain features. Situational Awareness and Prediction (SAP) works with the PATS sensor network to convert sensor data to information and to provide real-time collaborative situational awareness. The goal is to deliver a resource utilizing intelligent reasoning coupled with rule-based actionable intelligence using diverse knowledge fusion and modal trend forecasting. The SAP makes this data available to information sharing middleware using OGC standards.

The paper describes the architecture of both the PATS and SAP systems and how these two systems interoperate with each other. The SAP system works in concert with the Unified Incident Command and Decision Support (UICDS) information sharing middleware to provide data fusion from multiple sources. UICDS can then publish the sensor data using the OGC’s Web Mapping Service, Web Feature Service, and Sensor Observation Service standards. The system described in the paper is able to integrate a spatially distributed sensor system, operating without the benefit of the Web infrastructure, with a remote monitoring and control system that is equipped to take advantage of SWE.

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Mobile ad-hoc network, Multi-hop routing, Sensor network, Visualization.

1. INTRODUCTION

Sensor Web Enablement (SWE) refers to systems and technologies that present sensor data over the World Wide Web. As sensor and communication technology advances, sensor web-enabled systems become feasible in more challenging environments. For example, sensors can now be mobile and be distributed over large distances. Consider the problem of first responder tracking. In this application, the positions of all first responders (such as firefighters tackling a wildfire or rescue personnel responding to a large-scale disaster) have to be monitored from multiple remote locations, such as incident command centers. The positions of the first responders can be determined using GPS sensors carried by each person. If the remote monitoring locations have access to the World Wide Web, (WWW) it would be valuable to stream the GPS sensor data using SWE services to maximize inter-operability among diverse systems. However, at the locations of the sensors themselves (the first responders), the infrastructure of the World Wide Web may not be available. This is particularly true in the case of wildfires where firefighters may be deployed over an area of several hundred square kilometers, far from any Internet infrastructure, or after a disaster where existing Internet infrastructure has been
damaged. The chief challenge in such environments is how to integrate a spatially distributed sensor system, operating without the benefit of the Web infrastructure, with a remote monitoring and control system that is equipped to take advantage of SWE. Note that the initial idea of a sensor web did not necessitate the presence of WWW at the sensor level [1]. The SWE initiative has since assumed the presence of the WWW as the backbone of a sensor network [2]. Our chief contribution is a system that is able to bring mobile sensors arranged in ad-hoc network topologies into the currently existing Sensor Web framework. Multi-level sensor web systems have been developed [3] and sensor web languages have been defined for ad-hoc networks [4]; however, we present the first implementation details of a system that accommodates mobile sensors in arbitrary configurations and developed for a real-world application.

In this paper, we present two systems that together attempt to realize the sensor web vision of spatially distributed sensor resources working together to increase information availability. The Personal Alert and Tracking System (PATS) consists of a networked collection of custom-designed low-power wireless nodes which provides tracking of wild land firefighters (Figure 1). A PATS node is capable of transmitting sensor information and receiving visual/audible alerts and warnings over an extended rugged area. PATS nodes are capable of communication over several kilometers with burst rates of tens of kilobits per second. The nodes are equipped with onboard GPS, temperature, and accelerometer sensors with the ability to attach additional sensors as needed to each node. Mobile nodes form arbitrary network topologies and use a multi-hop packet routing protocol to relay sensor data to the command center. The multi-hop capability enables robust communication in a variety of environments by routing around natural and man-made terrain features. Embedded software on each node captures and processes sensor data and displays alert information to the firefighter.

The Situational Awareness and Prediction (SAP) system enables visualization of firefighter status at multiple remote locations such as incident command centers (Figure 2). SAP can setup two way alerts between mobile firefighters and the command center. Its visualization provides an integrated real-time mapping overlay that monitors, tracks, and reports location of large number of personnel to the command center. The visualization of firefighter locations is based on an open architecture (Google Maps) and uses OGC standards for interoperability.

PATS and SAP were designed at the Jet Propulsion Laboratory to meet the sensor web needs and requirements of wild land firefighters as defined by the Fire Research Working Group (FRWG) of the United States Department of Homeland Security (DHS). Prototype versions of the PATS node have been built and tested to characterize its communication capabilities. SAP has been tested to accept sensor data from PATS nodes over a bridge nodes and to present this data using OGC standards. SAP also has the ability to communicate with individual PATS sensor nodes from its web-enabled GUI. SAP can additionally post emergency management information, derived from PATS sensor data, to the Unified Incident Command and Decision Support (UICDS) network operated by DHS.

In this paper, we describe the architecture of both the PATS and SAP and show how these two systems interoperate with each
other. We describe existing systems with similar functionality and explain how PATS and SAP differs from these systems. We also present details from the preliminary testing of the PATS and SAP systems both in simulated deployments and in the field.

2. RELATED WORK

The SWE initiative of the Open Geospatial Consortium (OGC) standardizes data and web service interfaces to build an end-to-end “Sensor Web”. Broring et al. describe the initial specification of OGC’s SWE interfaces and how they have evolved over time [2]. However, in spite of these advances in SWE standardization, practical sensor web systems must still address issues not covered in the SWE specification. Knoechel et al. describe the difficulties faced by end-users of Sensor Observation Service (SOS) clients in searching for and accessing data from different sources [5]. Yu and Liu examine the challenges of integrating sensor data from heterogeneous sensor webs for scientific applications [6]. Thus operational sensor webs are often designed with SWE as only one part of the total design.

Disaster management remains one of the most practically important applications of web enablement of sensor resources. For example, Babitski et al. describe a SWE-based tool architecture that is designed to provide sensor data fusion during disaster management [7]. Ko et al. describe a Debris Flow Monitoring System where OGC’s SWE framework is used mainly to integrate various resources from different organizations (such as local governments and disaster prevention organizations) in Taiwan and to improve the decision making capacity in response to disasters [8]. The PATS and SAP system presented in this paper similarly uses OGC’s frameworks to distribute and integrate sensor data in standardized formats but local solutions are developed to collect the sensor data from the field. In particular, our use of mesh networking of mobile sensors is included in the framework of a SOS Observatory, as defined by OGC’s SWE Geoprocessing workflows [9].

The Geospatial Location Accountability and Navigation System for Emergency Responders (GLANSER) system is designed for both indoor and outdoor applications [10]. A node consists of a radio, battery, and a suite of navigation devices for embedded tracking. The nodes are carried by the firefighter. As in our system, GLANSER also uses mobile ad hoc mesh networking to continuously transmit this information to a base station at a command center. The Physiological Health Assessment System for Emergency Responders (PHASER) is a combination body temperature, blood pressure, and pulse monitoring system designed for emergency responders [11]. It is intended to be used in a networked environment.

3. SYSTEM ARCHITECTURE

3.1 PATS Sensor Web

The PATS sensor web is designed to relay information between widely distributed frontline wild land firefighters and remote command centers. The PATS web uses a multi-tier communication architecture (Figure 3):

Tier 1 is a local firefighter group with dynamic multi-hop routing. It consists of an ad-hoc mesh network of PATS nodes. A node is a portable device with sensors, radios, microcontroller, and embedded software. The nodes can autonomously self-organize in to a multi-hop network and relay sensor data to a Base station node. The distance between each pair of nodes can be up to 2km between firefighters for line-of-sight communication. The ad hoc routing accommodates random firefighter movements and an arbitrarily large firefighter group. The obstructions between firefighters are circumvented by a dynamic multi-hop protocol. Mesh networking at Tier 1 is conducted in the 902-928MHz radio frequency range.

Tier 2 is a long distance (10s of km) repeater network to a command center. The relay radio can transfer information from the multi-hop sensor network using a longer range, dedicated point-to-point communications path to a distant incident command center. Radio communication at 433 MHz will potentially be used for the long-range relay link.

3.1.1 Radio communication

At Tier 1, ad-hoc mobile multi-hop networking is used to collect sensor data from the handheld units and forward them to a central base station node. Multi-hop networking is also used to forward text messages from the base station to selected or all handheld units. Multi-hop communication is necessary in a web-enabled sensor network when an embedded sensor node is out of range of the nearest communication node with web access. In
such cases, the sensor data should be routed via intermediate embedded sensor nodes. In such a scenario, the spatial extent of the sensor web is limited only by the number of intermediate nodes (where the range is the number of hops times the radio range of a single sensor node).

The Collection Tree Protocol (CTP) is the specific multi-hop routing algorithm used in PATS [12]. In a collection protocol, data from all sensor nodes in a network is forwarded to a pre-defined set of base station nodes. CTP uses link quality estimates provided by the radio transceiver to determine how close neighboring nodes are. Each sensor node keeps track of which of its neighboring nodes is closest to the base station and data packets are sent out though this neighbor (this defines the next “hop”). CTP is a “best effort” routing protocol. It does not guarantee a 100% delivery rate but it utilizes several mechanisms to improve delivery reliability. High packet receipt rates have been reported in practice, ranging from 90 – 99.9% in test-beds with over 100 nodes [12]. CTP also enables route discovery and thus the sensor network can automatically adapt to changes in node layout. It can automatically re-route data as nodes are moved and new sensor nodes can join the network at any time.

Multi-hop communication is also used to send data from remote locations to PATS sensor nodes. The Dissemination routing algorithm [13] is used to distribute text messages to a set of selected sensor nodes. It is thus functionally the converse of the CTP routing protocol. The Dissemination routing algorithm is a flooding algorithm in that no route information is maintained at any of the nodes.

The specific implementation of the CTP and Dissemination routing algorithms that are used in PATS runs on the TinyOS operating system. TinyOS is one of the most popular operating systems for embedded low-power systems with extensive support for wireless communication and state-of-the-art networking algorithms [14]. TinyOS was originally developed at UC Berkeley and has since been extended to run on a variety of microcontrollers (such as the TI MSP430, ARM Marvell PXA271, Cortex M3) and radio transceiver chips (Intel/Chipcon, Semtech Xemics, Atmel). It has a diverse component library with sensor drivers, data acquisition, and storage algorithms. Thus, it is possible to use TinyOS to develop sensor webs that can operate a variety of sensors at different frequencies and data rates by choosing sensors and a radio transceiver with the desired hardware capabilities.

TinyOS is open-source software distributed under the BSD license and has an established support community. Several research and commercial motes are available with TinyOS as the operating system [15]. TinyOS is designed for embedded sensor
3.1.2 Hardware design

A PATS sensor node is designed to collect information from a variety of sensors, perform signal processing of the sensor measurements, transmit sensor data over the network, and receive messages from the network to be displayed to its user. The sensor node is intended to be carried by a person and so its location can vary in the sensor network. The PATS hardware design currently includes an ultra low power micro controller, sensors, and two radio transceivers. The microcontroller is from Texas Instruments low power 16-bit MSP430 family of microcontrollers. The microcontroller has four digital ports for interfacing digital sensors and the radio transceivers. The hardware architecture is designed to be upgradeable as the digital and analog ports of the microcontroller allow for additional sensors in the future.

The sensors are a 3-axis accelerometer, temperature sensor, and GPS module. The onboard accelerometer chip is capable of generating interrupts when it detects a free-fall or an extended period of inactivity. This capability is used to automatically generate and transmit an alert condition via the sensor web in case the user suffers a fall or is immobilized due to an accident. The user can also generate an alert condition by pressing a dedicated switch. Data from the sensors can only be accessed via the radio links, hence, instrument protocols, such as OGC PUCK, which have been defined for wired connections have not been implemented.

The two radio transceivers are configured to operate in the 902-928MHz and 415MHz range. The 900MHz radio is used for mesh networking at the Tier 1 layer while the 415MHz radio is to be used for a long-distance relay link. A 1” square, 128x128 pixel, color display is provided so that text messages can be displayed to the user. The node also contains a flash memory chip to store up to an hour of sensor data. The PATS node is powered using 2 AA batteries.

Most node components, including the microcontroller, radios, and sensors are integrated into a single circuit board (Figure 4). A separate daughter board houses the OLED display, Alert switch, display LED, and extension headers for the ports. Connectors on this board also provide for USB communication via a Serial-to-USB cable. All these components are supported by the TinyOS embedded operating system. A JTAG adapter is available for flash programming the microcontroller with embedded software.

3.2 Web Enablement with SAP

The overall objective of the SAP system is to provide a cost-effective nationwide capability to improve information sharing and decision making during emergencies and day-to-day operations. The major capabilities of this system are active surveillance of relevant information for each first responder, collaborative sharing between multiple front line organizations, geospatial mapping and fusion of multiple sensor web information, and real-time visualization of sensor information on portable devices. SAP empowers first responders with real-time collaborative situational awareness by predicting conditions and suggesting actions on how to respond to a situation. SAP can use portable devices as a means of providing lifesaving information to front line responders. The key challenges to designing such a system are:

1. How to provide only relevant situational awareness information to the user based upon their current role and to avoid information overload
2. How to embed state-of-the-art reasoning algorithms in a low-powered hand held device
3. How to fuse diverse sources of data into a unified reasoning system

Open Geospatial Consortium’s SWE is used to discover, access, and control the sensor web (Figure 5(a)). SAP uses JPL’s inference engine SHINE [16] to rapidly and efficiently analyze large volumes of data and to distill that data to a form that is sensitive to the context of the user using it. It integrates diverse data sources including a real-time sensor web interface. The SAP framework maximizes the relevant information content for the current context and displays it on a browser-based GUI (Figure 5(b)). It is also able to integrate data from other sources, such as the extent of a fire. Data is accepted in standard OGC formats for display along with sensor data.

The system is factored into discrete modules that can be readily integrated with existing SWE data sources. SAP can be visualized as a loosely coupled system implemented as a Server and Client as shown in Figure 6(a). The SAP Server acquires sensor data via a socket interface, caches acquired data in memory for interrogation, responds to requests for cached sensor data from the SAP Client element, and also manages a database of sensor data acquisition and interrogation context including authorized users, recognized sensors, and system operation incidents. New sensor system interfaces with entirely new information structures can easily be added to the service implementation module.
The SAP Client is a Web service that composes and delivers to SAP users, via their Web browsers, graphical representations of the sensor data acquired and managed by the SAP Server. It presents the user with a simple, highly functional graphical interface for the specification of the data to be displayed, the display of the requested data, and the annotation of that display in ways that can sharply increase the utility of the data to the user, including overlays, place marks, and whiteboard notes.

SAP works in concert with existing information sharing middleware, such as UICDS and Virtual USA, to provide data fusion from multiple sources. UICDS is a national middleware framework designed to support the National Response Framework (NRF) and the National Incident Management System (NIMS), including the Incident Command System [17]. SAP can provide first responders with active surveillance of relevant information fused with collaborative sharing of critical events between multiple organizations. Since the SAP Server is the venue in which all information acquired from sensor systems and delivered to users resides, it is also the site where we have implemented the UICDS Adapter that will enable it to function as a UICDS application as shown in Figure 6(b).

We have also developed an adaptive situational awareness GUI add-on to feed images to Virtual USA using KML (Keyhole Markup Language) or Flex API. This provides a multi-organization collaboration GUI add-on to Virtual USA and fingertip access to a variety of data sources on portable devices.

### 3.2.1 SAP user interface to PATS sensors

In the context of the PATS system, SAP is used to display the status and locations of firefighters at a computer in the command center over a Virtual Earth interface. PATS sensor data is displayed using SAP’s cloud-based database and web browser-based GUI. We use the Google Earth toolkit for overlaying sensor data on maps. SAP is configured to accept sensor data, GPS location, and alert status from the PATS ad-hoc network over a TCP port. For this purpose, a new Listener class was added to the SAP server (Figure 7). This new listener can handle a high volume of messages from PATS devices because it maintains an open TCP socket for the duration of a connection from a PATS bridge, rather than requiring that a new connection be established for each message. Moreover, open connections from multiple PATS bridges can be managed concurrently, so that the status of all firefighters operating in multiple PATS clusters can be shown on a single common Google Earth display.

The SAP GUI was modified to report the temperature, alert status, and GPS location of a given PATS node whenever the user “hovers” the mouse over the corresponding waypoint icon on the display (Figure 8). To decrease sensory overload, the placemarks used to indicate the location of each PATS node were modified to indicate quick-look status: normal, caution, or warning. Additionally, the user can specify a single PATS node to zoom the display in on automatically, in case the approximate location of the cluster is unknown.
3.2.2 Bridge between PATS and SAP
To transfer data between the PATS sensor network and the web-enabled SAP system, we developed “bridge” software between the two systems. The software (written in Java) executes on a PC connected to the PATS base station node and the base station node is connected to the PC using a Serial over USB link. The bridge software will read the bytes coming over the serial link, interpret the bytes as sensor measurements, and then relay them over a TCP channel to the remote SAP server. In addition, it will interpret text messages sent from SAP as messages to be sent using multi-hop routing to selected sensor nodes.

4. EVALUATION
Field-testing of the end-to-end PATS and SAP systems is underway. Prototype PATS sensor nodes have been manufactured and integrated with the SAP system. The prototype node has an embedded accelerometer, temperature sensor, and GPS sensor. An outdoor line-of-sight radio range of 2km is expected from this node when operating at its full Tx power. The combined system has been demonstrated in outdoor environments to firefighter working groups at the 2012 FEMA Urban Search and Rescue Workgroup meeting and at San Dimas Technology Development Center of the USDA Forest Service.

To study the scalability of the architecture and its implementation, tests have been conducted with simulated sensor data. Simulated sensor data from 25 sensor nodes operating at their maximum sensor sampling rate (one sample per 5 seconds) was generated and transferred to the SAP system over the PATS-SAP bridge. This data could then be visualized using the SAP’s browser-based GUI in its playback mode. Playback at 30 times normal speed was possible without any perceptible degradation in visualization quality. This test was conducted on a Firefox 9.0 browser running on a Windows XP PC with 2.66GHz Intel Xeon CPU and 3.25GB of RAM.

To test the scalability of the end-to-end throughput between the SAP and PATS systems, a test was conducted to ensure that system could scale to at least 50 nodes. The test showed that even at a packet rate of 10 packets/second, all packets were received. Thus, the system is scalable to at least 50 sensor nodes, each sending sensor data samples at the maximum sampling rate of one sample per 5 seconds.

To model the characteristics of the CTP mesh routing protocol in a variety of situations, we used the Castalia sensor network simulation software [18]. Communication nodes can also be mobile, as is the case with PATS nodes. Castalia is built on the OMNeT++ [19] discrete event simulator. Both Castalia and OMNeT++ are open-source software and available free for academic and non-profit use. The CTP model for Castalia is that provided by Colesanti and Santini [20].

Design curves showing the maximum packet rate that can be sustained as increasing numbers of PATS sensor nodes join the network were computed. The simulation parameters were set such that the radio communication range was set to 1000m with an ideal modulation scheme (i.e., there was no time-varying noise component). We generated data for nodes deployed in one of two configurations. In the Grid configuration, the nodes are arranged in a grid with cell distance set to 450m. In the Grid configuration, each node can directly communicate with only a subset of the sensor nodes (i.e. those within 1000m of its position) and multi-hop communication is required to move data from distant nodes to the data collection node. In the Row configuration, the nodes are arranged in a row with the data collection node at one end and the inter-node distance set such that each sensor node can communicate only with the two nodes on either side of it. These configurations are shown in Figure 9.

For each configuration, the number of nodes was varied from 2-50. For every such deployment, we increased the packet rate until the Delivery Ratio (DR, defined as the proportion of the packets transmitted from all nodes which are received at the central data collection node) dropped below 95%. Each run simulated 1000 seconds. The highest packet rate that provided a Delivery Ratio > 95% was then plotted with the number of nodes.

For the Grid configuration and Figure 11 shows the equivalent plot for the Row configuration. As expected, as the radio bit rate increases, the maximum packet rate also increases. The Row configuration is more restrictive in the sense that the Grid configuration can sustain a higher packet rate with the same number of nodes and bit rate. However, even with the Row configuration, at the lowest bit rate of 19.2kbps, a packet interval of 14 seconds could be sustained with 50 nodes (Figure 11). At a
bit rate of 38.4 kbps (where field experiments with the prototype PATS nodes indicate a line-of-sight range of 2km), the maximum packet rate is 3 seconds between packets with 50 nodes in the Grid configuration, and 5 seconds between packets with 50 nodes in the Row configuration.

Figure 11: Row configuration: DR vs. number of sensors at packet rate = 1 in 5 seconds.

5. CONCLUSIONS

PATS and SAP together form a means of integrating data from remote mobile sensors and presenting the sensor data using standard sensor interfaces. The prototype system provides tracking and autonomous alerts of wild land firefighters. The PATS system is able to organize mobile sensor nodes into a mesh network and relays all sensor data to a base station from where it is communicated to the SAP system. The Web-enabled SAP interface to PATS provides two way communications with sensor nodes which are beyond the Web infrastructure. SAP provides continuous visualization of firefighter status at a multiple locations using a specially designed web browser-based GUI.

SAP inputs sensor data into the UICDS information sharing middleware. UICDS can then publish the sensor data using the OGC’s Web Mapping Service, Web Feature Service, and Sensor Observation Service standards. The system described in the paper is thus able to integrate a spatially distributed sensor system, operating without the benefit of the Web infrastructure, with a remote monitoring and control system that is equipped to take advantage of SWE.

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7. REFERENCES