# AN ARCHITECTURE FOR LOCAL DECISION SUPPORT IN AD HOC SENSOR NETWORKS

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## ABSTRACT

The Intelligent Job Site is becoming a reality as applications (e.g., RFID for materials tracking, laser scanning and GPS for surveying and layout) using sensors and mobile computing devices are being developed and deployed commercially. This creates an opportunity for workers to access sensors in an ad hoc manner as they move through a job site. However, re-tasking and re-use of sensor data in a dynamic setting presents significant challenges including ad hoc identification of sensors in a local environment, the generalization of sensor information, and the use of such dynamic info for decision support applications. All these tasks require coordinated advancement of a variety of information and communication technologies. To achieve a generalized approach to make use of local sensor data, this paper describes a three-layer architecture which abstracts functionality into three corresponding tiers: a layer for sensor communication that handles physical communication between devices; a middle-layer for data processing and abstraction of sensor data from specific devices; and a top layer for decision support applications. At each of the three tiers in the architecture the level of abstraction increases, allowing for development of decision support applications at the top level that are not directly tied to specific sensors or computing devices. This paper demonstrates the usefulness and versatility of the proposed three-tier architecture by describing two safety applications envisaged for the Intelligent Job Site.

## KEY WORDS

Ad-hoc Wireless Network, Lightweight Footprint, Domain Ontology, Construction Safety, Decision Support

## INTRODUCTION AND MOTIVATION

Emerging field information and automation technologies provide the construction industry great opportunities to improve performance Applications include: laser devices mounted on equipments to prevent vehicle collision (Teizer et al. 2005), RFIDs and GPS

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attached onto material components for materials management (Jaselskis and El-Misalami 2003; Song et al. 2005), laser scanning devices or combination of GPS and smart sensors deployed on moving vehicles for collision detection (Riaz et al. 2006; Teizer et al. 2005), sensors equipped on construction equipment for danger alert to laborers (Nuntasunti and Bernold 2002), mobile devices (e.g., PDA and tablet) with embedded software and wireless communication capacity for inventory management and decision support based on collected data (COMIT 2003; Gaynor et al. 2005). These applications, among others, are constituent components of a vision for the "Intelligent Job Site" (FIATECH 2003).

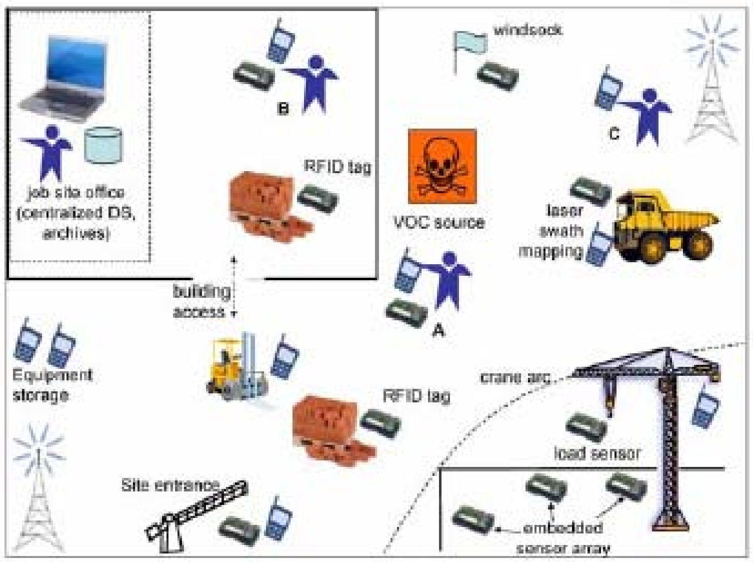



Figure 1: A representation of applications on the Intelligent Job Site

Figure 1 depicts a range of Intelligent Job Site (IJS) applications for materials management and safety, showing workers, equipment and materials immersed in an environment with multiple sensors, mobile devices, and wireless communication. While typically sensor- and mobile-applications in construction have been developed with a single task in mind (e.g., RFID materials tracking), figure 1 also helps to convey that a range of devices creates the possibility of re-tasking and re-use of application specific data. For example, the bottom right quadrant of figure 1 shows a crane with a load and position sensor. The data, used for crane load safety, could be reused by workers with GPS devices as they would be warned when entering the arc of the boom. Similarly, workers in the vicinity of a VOC emission could be warned with a proximity alert. VOC emission data could be combined with wind direction data from a local windsock to determine the likely direction of a plume, extending the range and specificity of warnings. These brief scenarios show that local sensor data, re-tasked and possibly aggregated with other data can provide a range of decision support applications to support field labor.

**THREE-LAYER ARCHITECTURE**

This paper proposes a three-layer architecture for distributed, (near-) real-time decision support in ad hoc sensor networks. The goal of the architecture is to provide local, customized decision support over ad-hoc sensor networks comprised of resource-constrained sensors and mobile devices. The architecture can be decomposed to minimize functions deployed by resource-constrained sensors and to increase functions on devices with sufficient resources (such as PDAs and portable laptops), making the network more efficient and creating a light data footprint on the network. As shown in Figure 2, the functionality can be abstracted into three layers: a top level of decision support for end users, called the Decision Support Layer (DSL); a middle level for data processing, called Data Processing Layer (DPL); and a bottom level for data communication among mobile devices and sensors, called the Sensor Communication Layer (SCL). An end user first selects small decision support applications ('chunks') in the DSL with functions correspond to his/her objectives. Data required by the chunks are decomposed into one or several query plans in the DPL. Queries are then sent to available sensors (accessed by the SCL) to collect data. This data is sent back to the DPL for processing and then passed on to chunks in the DSL. The architecture is meant to be generalized. A domain ontology at the DSL allows the DPL and the SCL to be domain-independent and also supports easy extension. Details are discussed below.

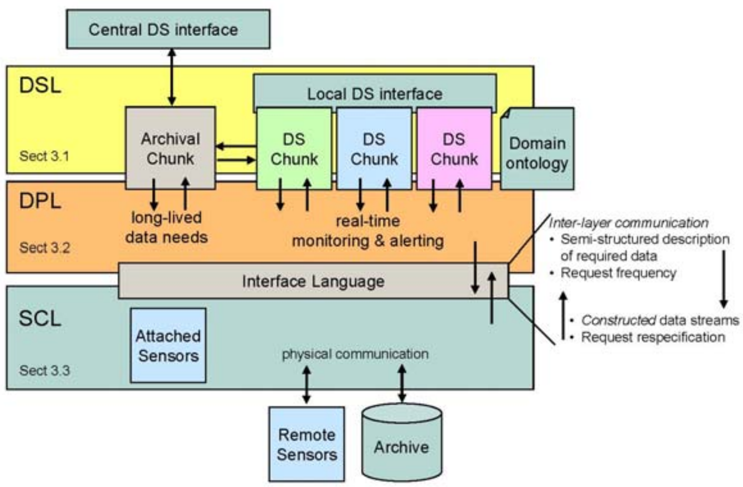



Figure 2: Three-layer architecture for decision support in ad hoc sensor networks

The DSL's functionalities are decomposed into small applications or chunks, each of which has a specific task, like monitoring VOC concentration and alerting users if the concentration exceeds a threshold. Such partitioning of applications eases deployment and reuse on a variety of devices. Chunks are tied to their respective domains and therefore need to be developed by domain experts. Different chunks developed by various people can be uploaded to an online chunk repository that is available through various sites and then be customized by users according to their unique circumstances and needs. Specifications such as function, input data, output data and device capability requirement can be attached to these chunks to make them ready for use.

Chunks can be categorized into two types: (1) local, near real-time decision support for a particular user (Decision Support (DS) Chunks); and (2) archival decision support for longer-lived information gathering with a more global perspective (Archival Chunks). DS chunks address tasks that require direct access to local information and real-time decision support. Whenever information is collected from a local environment, these chunks will respond to pre-determined events (e.g. user's entering the dangerous area under the crane in the scenario introduced before) quickly. The output of the decision analysis will appear on the local user's interface in the form of a value, a figure, or just an alert to trigger further action. DS chunks may also be aggregated to provide more complex or data intensive decision support. Using the VOC example described above, a single DS chunk may continuously monitor VOC emissions and alert when a threshold value is reached. A second chunk may be activated with an alert and combine the alert with wind direction data to provide information about the likely direction of a plume.

Archival chunks, on the other hand, collect data and information (e.g., location of materials pallets marked by RFID tags) available in the network but do not provide instant decision analysis to local users. The data will be uploaded to an archive whenever a connection is available. These chucks will periodically monitor the local information and decide what information to archive for later use based on pre-described needs.

When a user loads a chunk on his or her handheld device, the query texts associated with this specific chunk are evoked, extracted and passed on to a query execution engine within the D. The description-based query texts passed by the DSL describe the desired data and constraints on it. Query texts, are translated into a logic-based query plan by the query execution engine. The query plan not only describes the data requirements (e.g. data type and frequency) but also defines the operation(s) such as aggregation and filtering on the data. The completed query plan will then be sent to the SCL for resources discovery and data collection.

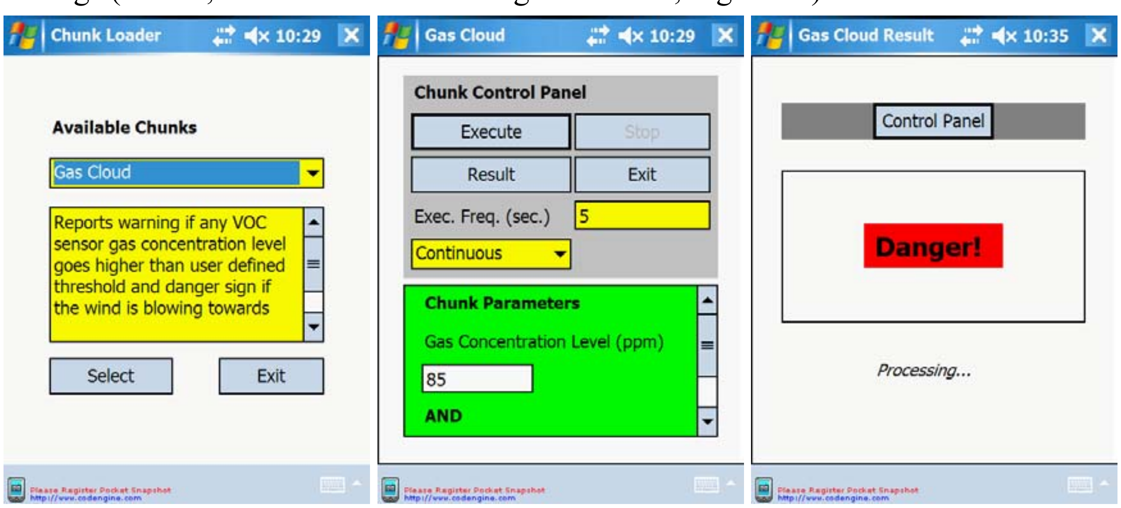
A domain ontology is deployed to customize the DPL and SCL interaction within the realm of interest. Within the DPL, the domain ontology is used to customize requests from the DSL, to interpret the information and data sent back from the SCL, and to connect this information with various domain contexts. This information is then passed on to chunks in the DSL for decision making. In general, the query engine and other components of the DPL and SCL are meant to be domain independent. By allowing query plans to be uncoupled from domain knowledge, developers for domain-specific decision support applications do not necessarily know the complex details and mechanism within the DPL/SCL. In this way, construction professionals and domain programmers can customize application to specific needs on sites without a large investment in understanding details of specific sensors and related devices.

The query plan passed on from the DPL is then executed within the SCL, which interacts with information-rich environments to discover proper resources and to provide the DPL with required data and information for processing. However, the query plan is unaware of physical sensors within the network, but only provides a description about desired data categories (such as VOC concentration in proximity), desired data types (single value or continuous value), frequencies of data readings (only for continuous data streams) or the sizes of result windows (for a snapshot). When the taking a query request from the DPL, the SCL will discover and communicate with the sensor sources to generate a requested stream. A routing approach called the Cross-layer Discovery Routing (CDR) (Julien and Venkataraman 2005) is used in our architecture to achieve this SCL's function . A connection between the sensors found and the query will be set up to provide required data for the DPL. The routing process is dynamic and real time, so as a worker with handheld device moves in the job site, the connection will be updated and linked to different physical sensors according to the worker's position.

## APPLICATION SCENARIOS

We have developed several IJS inspired applications that demonstrate the use of ad-hoc sensor network data within our proposed architecture. These applications are deployed within a simulated construction site using existing buildings (in a full scale deployment) or on a table top (scaled down for demonstration purposes). Our test deployment is mobile and contains a set of Crossbow Mica2 Motes with attached sensors and handheld PDAs with attached radios to communicate with the motes. Motes at present are quite small and various sensors can easily be deployed by placing them on the sensor boards attached to the motes. As such, the motes are versatile and support a range of test scenarios, making them ideal for prototype evaluation. In addition to the motes, the three layers – DSL, DPL, SCL – run on PDAs, providing a complete mobile implementation of the prototype architecture. Two sample applications for safety are detailed below:

Referring to the IJS pictured in figure 1, a potential safety application for workers is monitoring VOC emissions for safety. For the prototype, we generate a decision support chunk that communicates with one or motes that mimic a VOC sensor (a heat source/sensor is used to simulate emissions). The sample application interface can be seen in figure 3. Demonstrating that a range of applications can be selected and customized for each worker, figure 3a shows workers selecting a "gas cloud" DS chunk from the DS chunk repository on the handheld. Once selected, the DS chunk can be configured to define the gas concentration threshold before an alert (either using default value set by system on centralized computer or customize a different value) and monitoring frequency (Figure 3b). Once configured, the VOC detection chunk runs in the background of the PDA and continuously collects data from the local sensor environment at the desired frequency. As soon as VOC concentrations reach a predefined threshold, warnings (alarms, vibration or/and message on screen, Figure 3c) are sent to the user.




(a) (b)

Figure 3: User interface of VOC detection application

The VOC "gas cloud" chunk can be augmented with additional chunks to enhance decision support provided to users. An example is wind direction that can be used to guide users away from the dispersion path of a plume emanating from the VOC source. Figure 4 shows conceptually the devices used for such decision support, also depicting the range of functions within our architecture deployed on each device. Devices can have one to three layers, depending on their capability. Devices with high computing capability and durable power (e.g. workers' handheld PDAs in this example) can be equipped with all three layers, while energy constrained devices (sensors here) with lower computing capability can be equipped according to their limited functionality.

A second application concerns the danger posed by overhead movement of crane booms. In construction sites with limited sightlines, workers may inadvertently pass under the path of materials being hoisted by cranes. Based on such safety concerns, a decision support chunk was developed to allow workers working near a crane to be more aware of the crane's movement and to thereby reduce accident rates. In this application, the complex query plan is decomposed into simple queries within the DPL and the simple queries is passed on to the SCL to dynamically locate the sensors attached to various components of nearby cranes (e.g. crane boom angle, crane base location, load position). Information collected from the sensors is fused and returned to the DPL, where data will be further processed. Once determined, the dangerous areas are compared to workers' positions. The application can then alert any workers in danger. These alerts will appear on their handheld devices, along with a display of their distance within the crane's movement area. Figure 5 shows the progression of a worker moving inside the danger area of the crane (figures 5a & 5b) until clear (figure 5c). The current prototype works on a desktop application with live date from a model crane and scaled position data; live applications are envisaged that would depict site plans and the worker and crane position on the site plan. While not shown here, functions can be distributed among devices to limit use of limited computing and power resources. For example, rather than computing once for each worker, a sensor array leader (likely located on the crane) could store the aggregated data to be reused by multiple workers. Alternately, a single worker's handheld could make information about crane position available to other workers' devices.

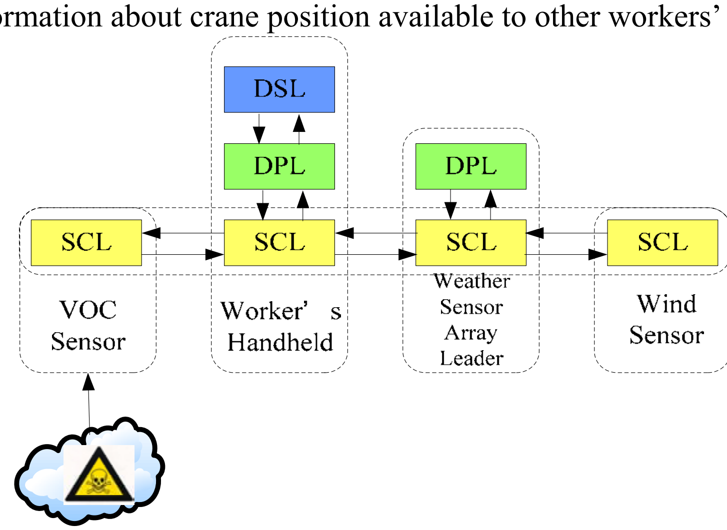
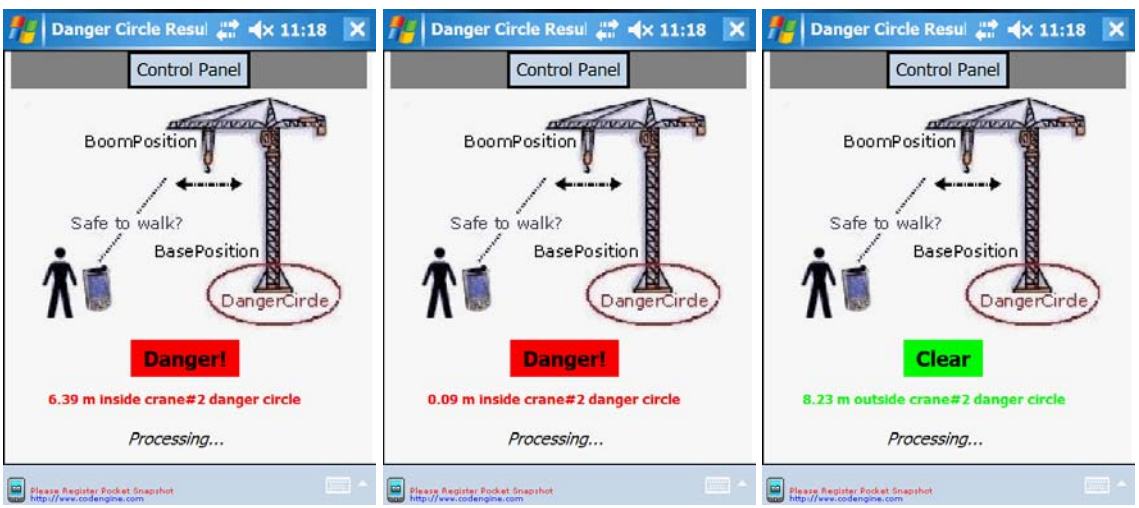



Figure 4: Example of deployment of VOC detection

## DISCUSSION AND RESEARCH CHALLENGES

Our prototype development of the architecture demonstrates its potential to support data abstraction, adaptation to dynamic environments, opportunistic data collection and coordination, and context-awareness. All these pose challenges for further development of our three-tier architecture. With respect to decision support, there are a range of mature approaches, several of which have been applied to real-time inference on sensor data. Such approaches include Bayesian Networks (Guo and Hsu 2002) and Petri Nets (Bulitko and Wilkins 2002). These methods are developed for well defined analysis with specific information requirements. However, the uniqueness, mobility, and distributed characteristics of construction projects make our decision support problems less well-defined as the data available may change depending on the sensors available. New decision support approaches are for support chunk description and operation, particularly with respect to missing/varying types of input data. Related challenges stem from the need to aggregate chunks to facilitate more sophisticated decision support applications.

Challenges related to the DPL stem from ensuring effective operation while maintaining the domain and application independence of the core engines. As the DPL is not necessarily aware of the physical sensors and is not designed with knowledge of specific chunks, generalized approaches to abstract query processing is a challenge. A related challenge stems from the ad hoc nature of sensor networks, which may require fusions of multiple data streams with different integration algorithms depending on data available in the SCL. A key feature of the SCL is opportunistic identification and interaction with available sensors to maximize data available for decision support. Beyond identification of an arbitrary number of sensors (that may change as a worker moves through a job-site), efficient interaction is a challenge. In an environment with multiple sensors but also multiple PDAs, it is desirable to limit bandwidth and power requirements on resource constrained sensors. Routing and data aggregation within the various devices that comprise the SCL are central research challenges.




(a) (b) (c)

Figure 5: Example deployment of crane movement warning

## CONCLUSIONS

The paper presents a new architecture for decision support within ad hoc sensor networks, where decision support functionalities can be decomposed into three layers (DSL, DPL, and SCL) and deployed into various devices according to their computing capabilities and network infrastructure performance. A key contribution of the three layer architecture is increasing levels of abstraction, which should both speed and broaden application development by limiting the need for domain programmers to have detailed knowledge of device specifics. The use of a domain ontology also allows deployment of the architecture in multiple industries. To-date, we have deployed the architecture on a few stylized IJS applications (two of which are detailed above). These prototype developments have served to validate the utility and functionality of our approach, and have helped to highlight research challenges for future development. On-going work seeks to expand the range and power of decisions support applications as well as underlying functionality of the DPL and SCL. Test evaluations on live construction sites are planned to check the power of the approach; generality will be tested by limited deployment in other domains.

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