A Pragmatic Approach to Smart Workspaces for Crisis Management

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ABSTRACT

We explore the nature and benefits of smart spaces from the perspective of the emergency management user, propose a design vocabulary and reference architecture for constructing feasible, robust and flexible smart spaces for crisis management, and offer some examples of how smart-space approaches might support crisis management.

Keywords

Crisis management, disaster, emergency management, smart spaces, ubiquitous computing, pervasive computing

INTRODUCTION

> "Design in sensing physical spaces should aim, foremost, to promote human-to-human interaction." (Darrow et al. 2007)

During a time when changes in the technical, economic, social and threat environments have put new pressures on facilities of crisis management and emergency response a new perspective on information technology has taken hold. That perspective goes by various names, including ubiquitous computing, pervasive computing, ambient intelligence, physical computing and the Internet of Things. One implication of this network-centric model is that the human-computer interface, previously concentrated on terminals or nodes, has exploded into inclusive environments called "smart spaces." In addition, the proliferation of highly capable mobile devices that are well equipped with sensors has created opportunities for those effective spaces to be extended to remote and variable locations forming "virtual spaces."

In this paper we will discuss the nature of smart spaces from the perspective of the emergency manager, propose a working vocabulary for pragmatic smart-space design, offer reference architecture for feasible, robust and flexible smart spaces for crisis management, and offer some examples of how smart spaces may promote human-to-human interaction under demanding conditions.

WHAT ARE SMART SPACES AND HOW SHALL WE KNOW THEM?

What would cause emergency and crisis managers to deem a space to be "smart"? Despite Mark Weiser's famous dictum that "The most profound technologies are those that disappear,"(Weiser 1991) much of the literature on smart spaces has concentrated on the technologies being injected into built environments. For example, the website of the European Institute for Innovation and Technology ICT Labs says that:

> "Smart spaces refer to built environments such as apartments, offices, museums, hospitals, schools, malls, university campuses, and outdoor areas that are enabled for co-operation of smart objects and systems, and for ubiquitous interaction with frequent and sporadic visitors." (Anon 2011)

Likewise, a description of a demonstration by the MIT Media Lab says:

> "'Smart spaces' are ordinary environments equipped with visual and audio sensing systems that can perceive and react to people without requiring them to wear any special equipment." (Wren 1996)

This is a worthwhile perspective, but we suggest that it is not always the most useful one at the interface between technologists and the practitioners of disaster, emergency or crisis management. From the pragmatic perspective of emergency responders, a space is only "smart" to the extent that it makes its occupants smarter, or at least more effective.

A complete list of the activities that occur in an emergency or crisis management workspace is beyond the scope of this paper, but certainly they include: monitoring the physical, technological and media environment for unexpected events and significant trends; allocation and control of limited resources; negotiation among self-interested actors with divergent goals and priorities; selection of strategies and planning of activities; deconfliction of plans and tasks; synchronization of activities; and documentation of events and actions taken.

The above list of activities was derived, however, not from an emergency management manual but rather from an introductory text on multi-agent computing systems (Wooldridge 2009). That congruence suggests that such systems might be useful in addressing some basic problems of crisis and emergency operations, provided we can find practical ways to connect them with human crisis managers. To assist in mapping technological possibilities to user needs we now suggest some vocabulary for discussing smart-space design and applications.

A USER-ORIENTED VOCABULARY OF "SMARTNESS"

The need for a common vocabulary is an axiom of emergency management. (Xu & Zlatanova 2007; FEMA 2008) While we have yet to compose a complete or enveloping model we have, in the course of interactions with emergency responders and disaster managers over several years, begun to develop a working lexicon for discussing smart space concepts with non-technical practitioners:

> **Space** – A continuum of opportunities for action, which might also be called a "workspace." Spaces are defined by the opportunities for action (capabilities) available to the individuals and teams that occupy them. Spaces may be physically enclosed, open or even discontinuous. "Virtual" spaces are created by the extension, sometimes limited or contingent, of capabilities across gaps in physical space.
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> **Smart** – Offering dynamic amenities and affordances that are responsive, considerate and/or instructive in ways that facilitate the users' needs, desires and goals.
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> **Actuator**—A device for effecting some change in the physical world or another logical system.
>
> **Sensor**—A device for detecting or measuring conditions in the physical world or another logical system.
>
> **Amenity** – A feature of a space that accommodates the users' needs, desires or goals.
>
> **Affordance** – A feature of a space that empowers a user to initiate or perform an action.[1]
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> **Responsive** – Said of an amenity or affordance that is dynamic in ways that respond to events or conditions.
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> **Considerate** – Said of an amenity or affordance that is dynamic in ways that accommodate users' individual conditions, situations, needs or preferences.[2]
>
> **Instructive** – Said of an amenity or affordance that is dynamic in ways that suggest or encourage certain directions for user action.

Note that we define the terms "actuator" and "sensor" at a different level of abstraction from the terms "amenity" and "affordance." The implementation of an amenity or an affordance may involve a combination of actuators and sensors, and an individual actuator or sensor may be used in the implementation of more than one amenity or affordance.

For instance, a shared map-based display of current conditions (often called a "common operating picture") can be described as a responsive amenity, in that it facilitates the users in a way that adapts automatically to changes

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[1] The term "affordance" has several senses in the language of design. The psychologist James Gibson, who coined the term, used it to refer to all the "action possibilities" within a specified environment. (Gibson 1977) Donald Norman reused the term to refer to those properties of a thing that determine how it might be used. (Norman 1988) Here we use it to refer to artifacts that enable goal-oriented actions, while addressing separately the degree to which they may be instructive as to its use or considerate of the users' needs and capabilities. Our working definition of the word "space" is, however, closely related to Gibson's sense of the term affordance.

[2] Here we broaden slightly the usage of "considerate" coined by W. Wayt Gibbs (Gibbs 2005) and adopted by Selker (Selker 2010) and others, who use it to refer to attentive systems that mitigate the effect of interruptions informed by a model of user context. We expand that definition to include other potential forms of consideration for individual users, such as adjustments in visualization style to accommodate a user's visual limitations, pacing of presentations to accommodate a fatigued user, etc.

in external circumstances. Its various user controls (pan-tilt-zoom, selection, etc.) can be deemed its affordances. A personalized version of the same display—a "user defined operational picture" (Mulgund & Landsman 2007)—can also be described as considerate to the extent its content or styling respond to the individual user's needs, desires or goals, e.g., by accommodating a visual disability or just a particular set of interests or responsibilities. A pop-up notification with an action button on a computer screen is a simple instance of an instructive affordance, as its appearance suggests a course of action that might not otherwise have occurred to the user.

Our usage of the word "space" likewise reflects a degree of abstraction that reflects the breadth and depth of emergency management practice. Indeed, we have encountered this non-literal use of the term "space" frequently in conversations with practitioners and design professionals who used it as a generalization and shorthand for a cluster of concepts such as "problem space," "design space," "decision space," and so on. This caused us to seek a non-physical working definition that more closely reflected how we found the term being used in practice.

We believe this sort of functional vocabulary for the design of smart spaces can help move the focus of design conversations from technology- toward user-oriented, while mitigating the risk of a reflexive, uncritical embrace of users' preconceptions (e.g., "I need a map on the wall and a bank of telephones.") In that way we believe it can serve as a creative tool for finding ways in which smartness might make a difference.

For example, once we start to think of the interior lighting for an emergency command vehicle as an amenity we may begin to imagine ways it might be made responsive; e.g., by adjusting to outside light levels to minimize night blindness and eye strain, or by dimming automatically at workstations where no one is present. We might make it considerate, possibly by providing individual users with lighting suited to their current task or even their individual circadian rhythms. And we might even make it instructive, perhaps by "popping" the light level briefly to alert occupants' of the interior workspace that some significant event has occurred.

Likewise, ongoing research into context-awareness in mobile application design for cellphones may enable us to make the affordances of a smartphone responsive by presenting location-filtered alerts, considerate by formatting audio and visual outputs for maximum effectiveness in the user's environment or for the user's current physical condition, or instructive by modifying the user interface to guide the user toward particular functions relevant to her or his current context.

Each of the above examples is, of course, entirely speculative, and serves only to illustrate the use of our working lexicon, both as a taxonomy for organizing development and as a creative tool for eliciting original ideas for applications and implementations by a juxtaposition of technical and human factors. Design from the perspective of technology has in our experience tended to yield fairly predictable results. The same can be said of a rigid devotion to users' expressed desires, which may be overly influenced by the technologies they already know. Referring to Christensen and other authorities on new product design, Robert Veryzer and Borja de Monzota observe that:

> "…technology push may lead to product solutions that fail to mach with customer needs, while reliance on customer input (e.g., market/customer research) can be problematic and even may undermine innovation." (Veryzer 2005)

By framing the design conversation in a language that straddles both worlds, but is constrained by neither, we hope to make creative design and analysis more productive.

But how can we move from these abstract concepts to usable real-world implementations?

A PRAGMATIC DIGITAL ARCHITECTURE FOR A SMART EMERGENCY OPERATIONS SPACE

> "Postulating a seamless infrastructure is a strategy whereby the messy present can be ignored, although infrastructure is always unevenly distributed, always messy." (Bell & Dourish 2006)

Abstraction is a key strategy for interoperability in complex systems. The voluntary subordination of subsystem optimization to "good enough" global standards, protocols and procedures has been one of the key success factors not only of the Internet (Hong & Landay 2001) but also of interoperable emergency communications. (Gavrilovska & Atanasovski 2007) In addition, providing a consistent cross-sectional view of a system can help mitigate against the sort of accidents that can occur in tightly coupled systems where the complexity and internal interactions can outstrip the operators' ability to comprehend or manage. (Perrow 1984)

From a pragmatic point of view, then, what combination of abstraction layers—or to put it another way, which architecture—might be most useful in designing, implementing and evaluating real-world applications of smart-space concepts to emergency operations centers, emergency command vehicles and distributed crisis management systems?

The interface between the real-world domain of sensors and actuators in physical spaces and the intelligent realm of context-aware, pervasive or ubiquitous computing is a critical one for several reasons. Designers have limited opportunities to standardize on the physical spaces to be served or the particular devices used to monitor and influence them, and only slightly more hope of any long-term standardization of the computing hardware and software in the "back room." Insertion of an abstraction layer can enable relatively loose coupling between those two domains and thus improve future prospects for refinement and reuse.

At first glance it might seem existing Internet protocols and architectures might suffice here. In practice, however, constraints of cost and energy supply for large numbers of small sensor and actuator devices can make a seamless end-to-end implementation of network protocols such as TCP/IP impractical. (Basten et al. 2003; Hnat et al. 2011) Instead, it often proves necessary to implement gateways between highly optimized (and often proprietary) subsystems and more flexible computing networks. Such gateways may also play an active role in the clustering of individual sensors and the local computation of summary or interpreted outputs.[3]

At the same time many reasoning systems and some control systems require temporal persistence of information about the state of the physical and/or computational domains, commonly referred to as "context." (Castro & Munz 2000) Data from sensors may need to be latched between readings to create a continuous representation of real-world state, and access to earlier measurements may be required for trend detection and adaptive modeling. At the same time, information on historic or pending tasks assigned to physical actuators may be necessary to subsequent computations. [4]

This interface between the physical and computational facets of a smart space often is addressed in terms of "middleware." Such middleware often combines persistence of context information with specialized functions particular to either the physical or computational domains. This hybrid functionality is usually intended to achieve efficiency, but the price can be a loss of flexibility and of interoperability with diverse and changing technologies on both sides of the physical/logical line.

For that reason we suggest that, in a pragmatic implementation intended for operational deployment, context should be treated as a distinct layer of abstraction. In practice many context models can be implemented with simple and generalized interfaces such as those of a conventional database. We have chosen to encapsulate context explicitly as a layer in order that the physical and logical domains may be linked via a well-defined, easy-to-inspect and easy-to-comprehend model. This, we suggest, will make smart-space environments easier to develop, debug, maintain and improve in production, and also more acceptable to users when used to support inherently complex and dynamic activities such as emergency response and crisis management.

Therefore we propose a simple reference model for the architecture of real-world smart spaces, particularly those deployed in support of emergency management.

In this architecture the smart-space system is composed of four functional layers:

- The User Space is occupied by humans and their tools, and is both monitored and modified by sensors and actuators at the boundary with the Physical Network.
- The Physical Network comprises data links using various protocols, as well as device drivers, cluster and action controllers and data pre-processors.
- The Context Model accepts update messages from the Physical Network and commands from the Reasoning System, publishes them to the opposite layer, and provides continual access to both a registry of current readings and tasks and a journal of previous updates and commands.
- The Reasoning System accesses the symbolic Context Model and generates commands to the Physical Network based on its various rules and goals. Multiple smart spaces, either physical or mobile, may be integrated by sharing some part or the whole of their Context Models.

This design is comparable to a typical three-tier system architecture except that the "business logic" implemented in the Reasoning System is positioned "behind" the Context Model instead of mediating between

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[3] Such gateways may also serve as trust proxies for the relatively simple devices beyond them in digital-signature based authentication schemes such as Anubis. (Buthpitiya et al. 2010)

[4] The inclusion of interpreted and historic data draws our use of the term "context" in the direction of the "situation abstraction" proposed by Anind Dey in (A K Dey 2001)

the client and database layers. This difference reflects the nature of the smart space as a dialog between humans and environmental events on one side and the artificial intelligence of the agents on the other. It might also be described as a "back-to-back MVC (model/view/controller)" design, except that the view and controller for the Reasoning System are simply an API to the Context Model.

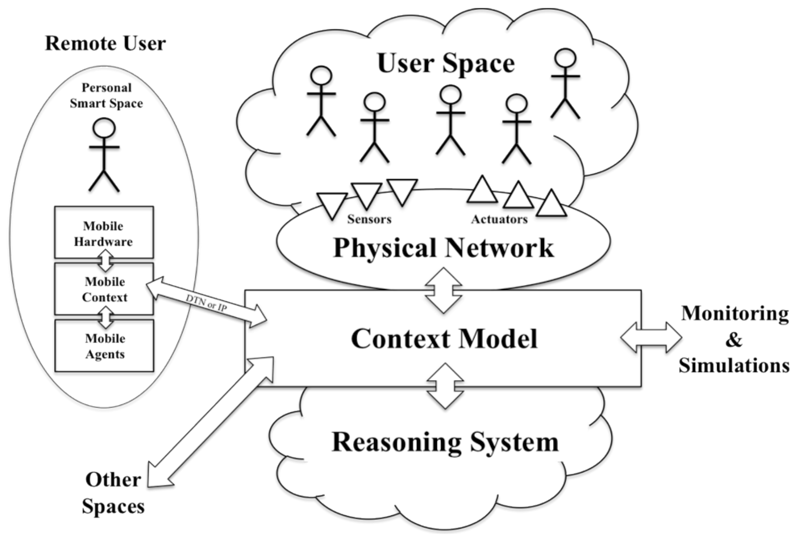

Figure 1 - Smart Space Reference Architecture

In the Crisis and Continuity Management Laboratory (aka the "Next-Generation Emergency Operations Center") at Carnegie Mellon University, Silicon Valley (CMU-SV) this architecture is being implemented as follows:

- The User Space comprises a dedicated enclosed workspace (a pair of instrumentation trailers provided by NASA) and also a large open area surrounding it, the CMU-SV Smart Spaces Lab in an adjoining building, various temporary workspaces (tents, command vehicles, etc.) that converge occasionally on the site to form a simulated field incident command center, and, via mobile devices and applications, the communities and region surrounding the CMU-SV campus on Moffett Field in the southern San Francisco Bay Area. Within this User Space the CMU-SV researchers are deploying a variety of sensors and actuator devices to provide amenities and affordances to users of the extended space.
- The Physical Network integrates devices in the User Space that are connected over a variety of wired and wireless links including WiFi, Bluetooth and low-rate 915MHz data radios attached to low-power Arduino-class microcomputers known as JeeNodes.(Wippler n.d.) [5]
- The Context Model is being prototyped using a fast No-SQL document database, MongoDB, that allows rapid prototyping of high-speed interprocess communication structures such as FIFOs and publish/subscribe services and that can raw and interpreted sensor data, device inventories and capabilities (e.g., Management Information Bs), and commands and data sent to sensors and actuators. In addition to providing as the communication link between the physical and reasoning layers and acting as the persistent "memory" of the system, the Context Model also serves as a diagnostic window into the state of the smart-space system and a portal for injecting simulated data into the system and monitoring system performance.
- The Reasoning System is being prototyped as a collection of discrete applications, mostly written in Python, and migrating toward a FIPA-compliant multi-agent system implemented in JADE and endowed with rules, machine learning and data mining capabilities.

[5] Initial experiments using the Robot Operating System (ROS) to implement the Physical Network showed ROS to be highly capable but somewhat unwieldy for rapid prototyping in a wide-area application. Current work utilizes library APIs and RESTful web interfaces to the MongoDB context model.

Note that all these particular technology choices are initial and provisional. One aim of the proposed architecture is to minimize future switching costs should other tools or techniques prove more attractive. For example, the Hermes widget-based context abstraction model (Buthpitiya et al. 2011) might be substituted for a database in the context model without losing the benefits of the abstraction.

Extending Smart Spaces Using Mobile Devices

Mobile devices put our functional definition of smart spaces to the test, as the spaces that mobile devices support are generally either personal or virtual. Personal smart spaces provide responsive, considerate or instructive amenities and affordances at the mobile user' physical location, chiefly responsive to their user's individual context (location, mode of activity, connectivity, etc.). (Roussaki et al. 2009) Virtual smart spaces extend a particular field of action (our working definition of a space) to include mobile users' locations, while extending the context model of the space to include information gathered by the users' and their devices.

Because our primary interest is in supporting collaboration and teamwork among occupants of functionally-defined spaces, our reference design includes mobile devices by connecting them to a "home" Context Model via the Physical Network (another reason to make the Context Model interface simple and generic.) Personal agent services and applications on the mobile devices (primarily running on Android devices in our experiments) will maintain a local context and reasoner, but also interact with the home smart space's context via a Physical Network connection. [6]

In some applications the mobile device may act simply as a remote sensor/actuator device with all reasoning being done remotely. At the other extreme we are actively investigating the use of Delay Tolerant Networks (Fall 2003) as a method for handling communication between the home Context Model and that on the mobile device in the event of disrupted communications.

THREE PRAGMATIC SMART-SPACE APPLICATIONS

> "System designers need experience to understand the implications of their design choices. But experience can be gained only by making mistakes…" (Rao et al. 2007)

The Disaster Management Institute at Carnegie Mellon University, Silicon Valley has embarked on a number of projects involving of smart-space methods to the improvement of emergency and crisis management. Here we describe three of our ongoing action research efforts through which propose to build a body of experience in implementing and operating an emergency management smart space.

Energy Management and Efficiency

The ordinary household thermostat is commonly cited as the prototype of smart-space technology; here we would categorize it (or rather, the heating and cooling system of which it is part) as a responsive amenity. Energy management has become a leading application for ubiquitous/smart-space computing, especially in the automation of large buildings. As energy costs rise and those of sensors and actuators fall it is becoming both desirable and feasible to control heat, light and other energy consumption at increasingly granular levels, frequently down to the level of individual rooms or even personal workspaces or operating areas.

Energy management frequently becomes a concern in emergency operations, either because the usual sources of energy have been disrupted, or because the workspace is away from conventional power source, e.g., in a mobile command vehicle or even a tent. (Kostka 2011) In the Continuity and Contingency Management Lab we are deploying a network of the JeeNode devices mentioned earlier to manage sensors and actuators that control lights, fans and other devices in order to optimize the use of our limited photovoltaic power resource.

Documentation and Just-In-Time Training

It is a truism of disaster management is that "no matter who you train in advance, somebody else will show up." Large crises and disasters are managed largely by what Alvin Toffer dubbed "ad-hocracies," special task-oriented organizations of actors who do not ordinarily work together in that particular way.[7] And even when an

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[6] This is directly comparable to the relationship between "front-end" and "back-end" users in the WORKPAD architecture. (Catarci et al. 2010)

[7] Emergency management structures such as the Incident Command System in the U.S. or the Gold-Silver-Bronze structure in the U.K. provide frameworks for the construction of such ad-hocratic teams.

operational team is pre-established and pre–trained, circumstances often require that they do things they have either never done before or at least have not done recently.

Earlier in this paper we introduced a notion of amenities and affordances. One example of an instructive amenity might be a system for presenting occupants of a smart space with just-in-time training and documentation, such as the failure-management-checklist feature mentioned in our previous discussion of ways to make smart spaces appear trustworthy. Likewise, a considerate affordance might be a voice-query system for requesting reference or tutorial information, a sort of local version of Apple's "Siri" speech interface.

In the Next-Generation EOC we use a Wiki for technical and procedural documentation, and post QR codes on devices and at doorways and workstations so the contents can be pulled to mobile devices when needed. We are now investigating how a smart-space system might take the initiative on the basis of context to push that same information to users immediately when or even before it's needed.

At the same time a number of other CMU-SV researchers are investigating the uses of mobile context-aware agents to provide decision support and enhanced collaboration in the field, for example. We will be drawing on their experience to design a context model that can be shared by both co-located and dispersed users.

Digital T-Cards

The "T-Card" is a time-tested paper form for recording and tracking the status of resources. In the United States the T-Card is a standard form (FEMA n.d.) mandated for use in the Incident Command System. The discovery, identification and tracking of resources in emergencies have consistently proven problematic. (Rao et al. 2007) A variety of systems using RFID have been developed to try to address this challenge, but the limited power and data capacity of low-cost RFID tags, along with their sparse standardization, has limited their utility. (Kaur et al. 2011). In effect, many of these systems yield only a marginal improvement on the traditional paper T-Card.

Members of CMU-SV's Disaster Management Initiative are designing a more capable integration of wireless mobile devices with an updated set of XML document specifications for resource management being developed for the U.S. Department of Homeland Security by the OASIS standards organization. The Digital T-Card agent will maintain a digital context on the mobile device for an associated person, vehicle or other physical asset that can be updated continually by sensors in and around the mobile device. The agent will make this current "context" for the asset available for polling and forwarding from fixed or mobile interrogators to resource management systems and smart spaces using Delay Tolerant Network protocols.

CONCLUSION

> "Ubiquitous computing is unusual amongst technological research arenas. Most areas of computer science research…are defined largely by technical problems, and driven by building upon and elaborating a body of past results. Ubiquitous computing, by contrast, encompasses a wide range of disparate technological areas brought together by a focus upon a common vision. It is driven, then, not so much by the problems of the past but by the possibilities of the future." (Bell & Dourish 2006)

In this paper we have attempted, above all, to begin to find synergy between idealism and pragmatism, theory and practice, technology and user, in the search of improved designs for fixed and mobile emergency and crisis management workspaces. We have embraced the promise of smart spaces, ambient intelligence and "ubicomp" while at the same time striving for a realistic and achievable program of real-world development and evaluation in the demanding domains of emergency response, disaster relief and crisis management.

We have suggested a user-oriented language for discussing the possibilities of such applications, and a pragmatic reference architecture for the real-world deployment of smart-space concepts. We also have described several ongoing projects that are implementing that architecture within a continuing program of action research and community engagement between academics and emergency management practitioners.

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