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New technology applications in hazardous materials operations

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ABSTRACT

The authors have been investigating novel ways to apply technology to enhance response to fast-paced, complex, hazardous materials (HAZMAT) incidents. Although there are many uses of Global Positioning System, Radio Frequency Identification, simple radio frequency transmitter/sensor devices, and multitouch display technologies, these technologies have only made their way into the HAZMAT community in limited ways. Based on an investigation of the technology needs of HAZMAT responders, the authors developed an approach to combine these technologies to address the observed safety, situation awareness, and efficiency shortfalls. This article describes the proposed approach and provides the results of an investigation into its acceptance and likely utility. During low-fidelity prototype-based user tests and structured interviews, certified HAZMAT responders gave high scores to the usefulness of the proposed functionality and its likely helpfulness in maintaining safety.

Key words: emergency response, low-fidelity prototyping, user testing, information technology, HAZMAT

INTRODUCTION

The hazardous materials (HAZMAT) domain is a mature domain with a nationally recognized training curriculum[1] that is practiced in accordance with the standardized Incident Command System.[2] Despite the field's maturity, the International Association of Fire Chiefs' First Vice President, Jeff Johnson, called for "improved national preparedness for the response to HAZMAT incidents" when he appeared before the US House Transportation and Infrastructure's Subcommittee on Railroads, Pipelines, and Hazardous Materials in May 2009.[3]

Our goal is to propose technology solutions for HAZMAT incident response that will facilitate situation awareness, increase effectiveness, and improve safety. To accomplish this goal, we first needed to gain a thorough understanding of the needs of HAZMAT personnel. We interviewed HAZMAT responders and observed three exercises, the longest of which we recorded and analyzed in detail in Ref. 4. We re-examined the data from the longest exercise, as presented in the next section, to guide our current design work.

In our 2008 study, we concluded, as confirmed by the analysis in "Technology needs analysis" section, that there is a need to help responders track assets (both people and equipment) and better understand the current state of the evolving situation. Using technology to address these needs aligns with the International Association of Fire Chiefs' statement that "high-tech instruments should be utilized by local HAZMAT teams."[5] Our approach also seeks to ameliorate the National Research Council's concern that "disaster management organizations have not fully exploited many of today's technology opportunities."[6]

This article describes a set of technologies that we chose in an effort to provide complementary benefits to HAZMAT responders. Further, this article documents user testing of the technology concepts via a low-fidelity prototype designed to provide early feedback, prior to the expense of full-scale implementation. Specifically, we investigated whether the technology approach would provide useful functionality that would be likely to increase safety.

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Related work

Products such as the HazMaster G3 by Pocket Mobility, Inc.,[7] are described as being "decision support systems" (DSSs) for HAZMAT incident response. These systems provide a means of quickly looking up information on chemicals. These palmtop- or laptop-based applications take the place of the paper job aids that HAZMAT personnel have long used. While the current state of the practice is to provide DSSs for individuals making decisions about chemicals, we seek to help groups be better informed and make improved decisions at the command and control level.

There have been some research investigations into command and control of hazardous materials emergency response (HAMER). Zografos et al.[8] created a framework for developing DSSs for HAZMAT, which they subsequently used to develop an HAMER DSS. They used a questionnaire to perform a context analysis, function identification, and task analysis, and they followed these with a survey of relevant existing and new technologies. Similar to software engineering methods, their functional identification involved specifying input data, processing, and output. However, requirements for information synthesis (as opposed to a simple list of information requirements) and an assessment of the priorities for data presentation and alerting are missing from their work.

Bourne et al.[9] more directly tackled the problem of synthesizing information for the HAZMAT emergency responder. They developed a proof-of-concept prototype HAZMAT-related DSS called Focused Analysis Linking Chemical and Community Data to Operational Needs. However, this prototype is aimed toward an individual decision maker, as opposed to aiding a group of collaborators.

Our approach is different from these efforts that are aimed at automating handbooks or providing personal decision-making aids. Instead, we aim to develop approaches for comprehensive command and control tools that take advantage of an integrated suite of technologies to synthesize information and help groups make decisions.

Our research is the first to take the approach of combining the following four technologies for the benefit of HAZMAT responders: Global Positioning System (GPS), Radio Frequency Identification (RFID) tagging, simple radio frequency transmitter/sensor devices called Sun™ SPOTs, and multitouch display devices. In particular, table-based, multitouch displays have been used in flood emergency response[10] and command and control,[11-14] but not for HAZMAT incident response. This article's chief contributions consist of the novel technology approach and the results of user testing that can guide implementation of technologies to benefit HAZMAT response.

It is important to note that although all of the technologies described in this article exist, they do have limitations, and it is just as important for emergency responders to understand the limitations of their equipment as well as the capabilities. For example, the current GPS does not work indoors or underground. Radio transmissions through heavy material are also problematic for networking devices. Fortunately for emergency responders, there are much larger markets and financial motivators driving this technology. Cellular phone companies are quickly becoming the next Internet service providers, and they are discovering new ways to digitize and modulate wireless signals through buildings. The ubiquity of GPS in cell phones for E911 services has significantly reduced the size, price, and complexity of these chipsets while increasing their accuracy. Also, there is significant funding and interest from the US military for indoor-capable GPS, and prototype systems are currently in testing. Based on our vision and the results that we present in this article, we hope that the technologies discussed in this document represent near-term solutions to long-standing problems in HAZMAT response.

TECHNOLOGY NEEDS ANALYSIS

We observed a day-long HAZMAT exercise with approximately 30 participants whose purpose was to practice identifying the nature of and responding to a simulated HAZMAT incident. We taped the utterances of two key personnel and all of the radio traffic and transcribed the tapes, which resulted in 15.75 hours worth of recording typed onto 139 pages, broken into 3,841 conversational turns. A qualitative assessment of this data can be found in Ref. 4.

Using an approach informed by conversation analysis[15] and grounded theory,[16] we analyzed the transcripts for this phase of our investigation by first finding all utterances that indicated problems and then characterizing them, with the goal of determining the types of problems that were most often discussed by the responders themselves as they performed their tasks. This new assessment differs from the analysis in Ref. 4 by focusing solely on the statements that indicate negative conditions or actions. We created a new set of categories to characterize these negative utterances as follows:

- *Location, status, and usage of equipment*: For example, a responder described the consequences of erroneously keeping a piece of equipment in a plastic bag: "The MultiRae was always malfunctioning. It would not monitor the atmosphere since it was in the bag."

- *Procedures for performing tasks*: One example of a procedure that was not working was monitoring the state of the air near the decontamination station. In the words of an exercise participant: "The air monitoring that we were doing at the end in the decon[tamination] line for ammonia was inadequate."

- *Radio performance issues*: A responder noted difficulty hearing another responder: "It seemed like there was a radio problem 'cause it seemed like that you couldn't hear whatever M. [was saying]," for example.

- *Roles and who is acting in what role*: The following exchange illustrates confusion over who is performing the planning role.

Man 1: Do we need planning now?
Man 2: No. We already reassigned her.
Man 1: Someone's got it? Someone . . . did someone take over planning?
Man 2: I did.
Man 1: OK, cause it got dumped and I'm just looking at: did it get picked up?

- *The status of the current situation*: In the following example two exercise participants discuss how the responders in the "hot zone" did not maintain awareness of the elevated level of dangerous chemicals they were being exposed to.

Man 1: Nobody really went over and read your *[two words garbled]* exposure and your extremes.
Man 2: Yeah, no one really . . .
Man 1: They didn't know to get outta there.

- *Chemicals and their properties*: In this example, the responder was unsure of the level of exposure that is acceptable for ammonia: "Should be able to go up over a hundred parts per million . . . I'd have to look it up."

- *Any other problems*: A few problems did not fit into the above categories, such as difficulty keeping track of documentation in electronic form: "I forget—where does this exist in electrons right now?"

Table 1 shows a breakdown of statements indicating confusion, mistakes, misunderstandings, or other problems as they pertain to these categories. Table 1 should be viewed in light of several limitations. First, despite using high-quality recording equipment, a few of the words were unintelligible. Second, we did not capture all utterances of all 30 personnel, and therefore, we undoubtedly missed interesting discussions that pertained to problems. Third, while frequency of occurrence is one indicator of importance, we cannot make firm assertions regarding the relative priority of problems based on how many times they were discussed. Finally, the exercise participants did not always realize what they did not know, so they did not talk about these unacknowledged problems. We mitigated a potential limitation by ensuring that our research team included an HAZMAT subject matter

Table 1. Problems discussed in transcript		
Problem type	**Number of turns**	**Percent of total**
Equipment	150	27.2
Procedural	129	23.4
Radio	110	19.9
Roles	69	12.5
Situation	60	10.9
Chemicals	28	5.1
Other	6	1.1
Total	552	100

expert who helped the team to attain a good understanding of the significance of what was being discussed. Also, we observed other exercises to confirm that the kinds of problems we observed in this exemplar exercise were typical of HAZMAT situations.

For all its limitations, field data have great value. Holtzblatt and Jones,[17] for example, noted that interviewees did not mention important aspects of their work when interviews were conducted outside of the normal work environment. Examining the transcripts in detail yields a data-driven, objective look at the challenges experienced by a group of real-world HAZMAT responders. By cross-checking the results with observation notes from other exercises, we are confident that we have identified important problems experienced by HAZMAT responders.

Recent technologies hold promise for addressing a number of these problems. The results in Table 1 indicate that more than a quarter of problem statements could be eliminated if responders had access to technology that helped them to know what equipment is available for deployment or is already deployed, whether it is operational or compromised, and where it is located. Any means of showing responders the status of the situation, the procedures that are currently being executed, and the plans for the near future* have the potential to eliminate approximately a third of the problem statements. Further, providing information on who is performing what role and where they are located at any given moment may eliminate one-eighth of the problem statements. Because of the potential for technology to help in these areas, we created a vision of how responders could be better supported. We then created a low-fidelity prototype of this vision and tested it with HAZMAT responders to obtain guidance for future technology design decisions.

TECHNOLOGY VISION

Our vision started with the desire to dramatically assist responders in scenarios such as the following:

> The Lowell, Massachusetts, Fire Department hazardous materials team and an engine crew respond at 2:00 a.m. on a cool September night to an overturned propane truck at the intersection of University Avenue and Colonial Avenue near the Merrimack River Bridge. The propane is leaking onto the roadway and ground. Additionally, one of the truck's two saddle-style gas tanks is leaking diesel onto the ground. The diesel is pooled into the south corner of the intersection near a storm drain that empties into the river.

Now assume that the response to this incident takes place after four enabling technologies were deployed.

> The HAZMAT truck rolls up and opens the back door. Two responders enter the rear of the vehicle and leave with self-contained breathing apparatus (SCBA), personal protective gear, and MultiRAE meters (sensors that detect the presence of hazardous materials). The truck's doorframe is equipped with an RFID reader that senses that these tagged items are leaving the truck. The RFID readings are wirelessly transmitted to a base station and from there to a new HAZMAT command and control system. The MultiRAE meters

*This is an example of Endsley's[18] Level 2 and Level 3 Situation Awareness: comprehension of the elements of the environment and projection of their state into the future.

are equipped with GPS devices and "Sun™ SPOTs" that wirelessly send the meter's readings and the meter's GPS position to the base station. The base station then sends this data to the command and control system. The responders clip Sun™ SPOTs onto their belts so that, if they go down, the Sun™ SPOTs' accelerometers sense that the responder is not moving and sends that information back to the base station. Meanwhile, the incident commander requests mutual aid from Chelmsford, Massachusetts, and their estimated time of arrival of 7 minutes is computed by their vehicle's GPS system and sent directly to the command and control system.

We chose these technologies because of their potential to address several of the problems identified by our observation sessions while being affordable and practical.

For example, RFID tags are already in widespread use in HAZMAT operations, although to track the materials themselves rather than the incident response team assets.[19-22] The tags are currently available in sticker form and are now extremely inexpensive and easy to procure. The reason for putting a GPS reader on the door of the truck is to eliminate the need for responders to have to do anything extra to record the fact that a piece of equipment has left the HAZMAT vehicle. During observations, responders often experienced high workload conditions that led us to believe that they would not welcome new technology if it came at the price of slowing down operations.

GPS systems are often installed on HAZMAT vehicles, but the new twist consists of automatically incorporating this GPS information into a command and control system. Also, GPS systems have not tended to be installed on equipment other than vehicles. We envision using readily available commercial GPS units.

Sun™ SPOTs (Small Programmable Object Technology; Sun Microsystems, Inc.) are approximately 2″ by 1″ by ½″ digital pass devices with a radio and accelerometer that can be hooked into the serial output of sensors such as MultiRAEs or Geiger counters. The Sun™ SPOTs do not need an existing wireless network infrastructure. They form an ad hoc network with each other and with the base station, communicating with each other and acting as repeaters when needed.[23] Their ability to work without existing infrastructure is critical to their potential utility, as responders cannot count on incidents occurring in locations that have functioning wireless networking already in place. Sun™ SPOTs are available off-the-shelf for an inexpensive price when purchased in quantity.

The HAZMAT command and control system is envisioned to consist of a set of tabletop-based and handheld multitouch displays with prototype interface designs that we created as part of this project. We developed a paper prototype of the tabletop system intended to accommodate Incident Commanders (ICs), operations personnel, planners, and logisticians, as described in the next section.

HAZMAT COMMAND AND CONTROL PROTOTYPE

Multitouch tabletop displays invite collaboration in a way that a group of individuals' laptops do not. People are used to working together around a table, but if they each have laptops open in front of them, the effect is of several information islands rather than a shared experience. HAZMAT response is an inherently collaborative endeavor: operations, planning, logistics, and decontamination teams must work together, often along with fire/rescue responders and/or with Federal Emergency Management Agency (FEMA) personnel. Although this article documents the test of our designs with individual users, eventually our goal is to recommend technology for teams of HAZMAT responders. Ours is the first attempt to design multitouch displays for HAZMAT usage.

The prototype multitouch display contains four tabs at the top of the display corresponding to four screens designed for use by the IC, operations team, planning team, and logistics team, respectively. The first three tabs contain an area dedicated to a map, which is shown in Figure 1 (illustrating the IC's screen) as a top-down imagery map focused on the area identified in the scenario.

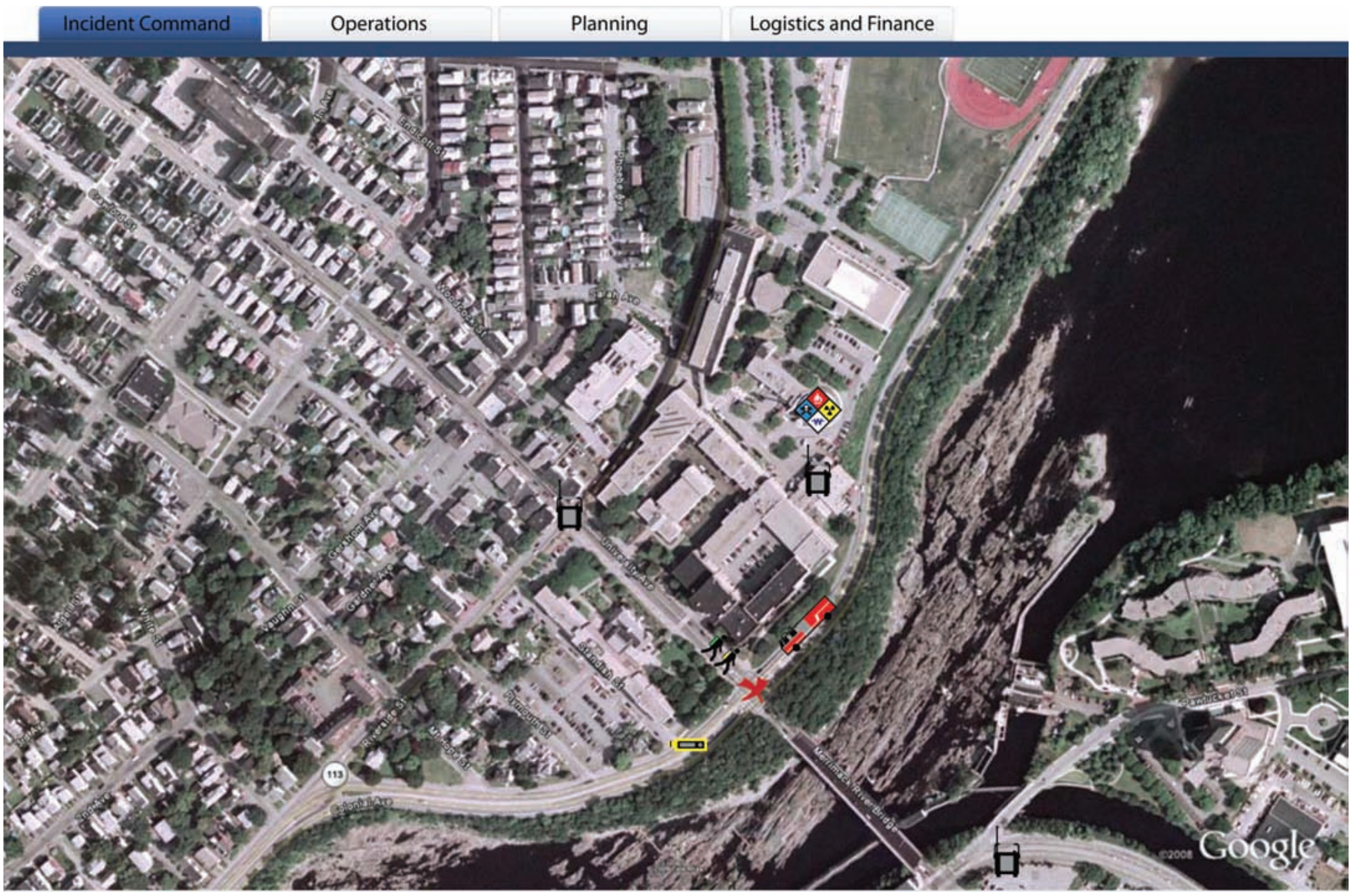


Figure 1. Incident Commander's command and control screen, showing locations of people, equipment, and hazardous materials. Tapping on any of the icons displays additional information about that object.

We provided participants with a set of icons printed onto clear acetate and cut apart so that they could be placed on top of the map at the desired locations. The icons are reproduced in Tables 2 and 3.

The operations team's screen is similar to the IC screen, except that, on the right-hand side of the screen, there is a panel listing resources (people and equipment) currently in use. The list is shown as a tree, with categories either collapsed (showing a "+" to indicate that more detail is available) or expanded (showing a "−" to indicate that there is no further hidden detail). This screen is illustrated in Figure 2.

The planning team's screen, shown in Figure 3, includes not only assets that are currently being used but also those that are en route or available to be deployed.

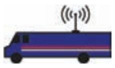
Finally, the logistics team screen, illustrated in Figure 4, is not map based. It consists of a list of all assets (both people and equipment) and their status. The right-hand panel is the same as on the operations' team screen and shows a list of only the assets that are currently in use.

USER TESTING METHOD

User testing consisted of a scripted interview combined with a usability test. In general, participants in a usability test perform a set of preplanned, realistic tasks under controlled conditions. By having all test participants perform the same tasks, evaluators can look for patterns that reveal portions of the interface that are more or less difficult to use.

Because it did not make sense to create an expensive, detailed prototype when we did not know whether our technology approach would be useful, we created a paper prototype for the usability test. Paper

Table 2. Icons and their meanings

Icon	Meaning
	APD2000 sensor without radio signal; a chemical/biological detection device.
	APD2000 sensor with radio signal; a chemical/biological detection device that is transmitting.
	AreaRAE sensor without radio signal; a remote gas detection device.
	AreaRAE sensor with radio signal; a remote gas detection device with transmit capability enabled.
	Barrels of hazardous materials.
	Command truck.
	Fire truck.
	Geiger counter without radio signals; a radiation detection device that is not transmitting.
	Geiger counter with radio signals; a radiation detection device that is transmitting.
	HAZMAT location (alternative #1).
	HAZMAT location (alternative #2).
	HAZMAT placard with colors.
	HAZMAT placard with icons.
	HAZMAT truck.
	MultiRAE sensor without radio signals; a five gas detection device that is not transmitting.
	MultiRAE sensor with radio signals; a five gas detection device that is transmitting.

prototyping "is a variation of usability testing where representative users perform realistic tasks by interacting with a paper version of the interface that is manipulated by a person 'playing computer'."[24] Besides being less expensive to prepare for and conduct than usability tests using higher fidelity interface prototypes, paper prototyping encourages participants to share their suggestions for radically different design approaches. The very fact that the prototype is executed in paper informs participants that there is little vested interest in a particular design because it can be changed with a stroke of a pencil instead of through many hours of recoding and debugging a computer application. Thus paper prototyping is an ideal approach for obtaining user feedback on early concept exploration.

We recruited five participants for user testing. While five is not a large number, previous research has shown that five participants can expose 80 percent of the usability problems.[25] With more than five participants, the number of additional problems asymptotically approaches 100 percent, with very little added benefit resulting from the time and effort required to test with each participant above five.[26]

Test participants

Four men and one woman participated who have between 10 and 35 years experience in emergency response and were trained in HAZMAT operations. Three of the participants were HAZMAT response trainers and another participant was an HAZMAT Safety Officer for a municipal fire department. The fifth participant was a Technical Information Specialist trained in HAZMAT Operations with FEMA. Two of the participants were in their 30s, two were in their 40s, and one was more than 60.

All participants have more than 5 years of experience with computers running Windows, and two also have 5 or more years of experience using Macintosh computers. Two participants considered themselves to have "moderate" computer expertise, defined as "I do a lot of my regular work or leisure activities on a computer" and three identified themselves as "experts": "I troubleshoot and upgrade applications or operating systems."

Table 3. Icons including human figures and their meanings

Icon	Meaning
	Person with APD2000 sensor, a chemical/biological detection device.
	Person with AreaRAE sensor, a remote gas detection device with transmit capability.
	Person with full air tank.
	Person with half-full air tank (alternative #1).
	Person with half-full air tank (alternative #2).
	Person with low air tank (alternative #1).
	Person with low air tank (alternative #2).
	Person with low air tank (alternative #3).

Test procedure

Testing took place at each user's workplace over the course of 60 to 90 minutes. We started by reading a script introducing the test. Next, the participant signed an informed consent form and filled out a demographics questionnaire.

We then provided a partially scripted verbal description of the four enabling technologies (Sun™ SPOTs, RFID, GPS for vehicles, and multitouch tabletops). The description included a demonstration of two Sun™ SPOTs communicating with each other. We handed a summary sheet of these technologies to each participant to refer to throughout the test if desired.

During the next step, we handed the participant with a description of a scenario (the overturned propane truck situation referenced in the Introduction section), which we also read aloud. We told the participants, "If the scenario isn't detailed enough for you, make reasonable assumptions to fill in the blanks when you are asked to think about using these new technologies to respond to the incident."

We trained the participant on the multitouch command and control interface, including providing a written description that they could refer to during the testing. This training consisted of describing the icons and the major components of the four screens corresponding to four tabs on the tabletop display. We provided training because we were more interested in understanding the system's potential ease of use for people who would use the system on a regular basis, rather than determining whether the system would be easy to learn.†

Next, we asked the participant to refer to the scenario and assume the role of an IC. We asked him or her to use the paper prototype, assume that the other technologies discussed previously were available, and to take the initial steps to resolve the situation. As they were doing so, we asked interview questions regarding information presentation and functionality (particularly functionality that may be missing), attempting to ask each question when it was relevant to their progress in completing the task; however, we phrased each question so that it did not influence their progress toward task completion. We then asked the participant to assume that they were the operations team lead and repeat the task. Similarly, the final two tasks focused on the planning team lead and the logistics team lead.

Participants were asked to fill out two questionnaires regarding the relative value of having different types of information (a ranking exercise) and regarding their subjective assessment of the prototype system.

†Note that we investigated the ease of learning of multitouch interfaces for controlling remote robots in Ref. 27.

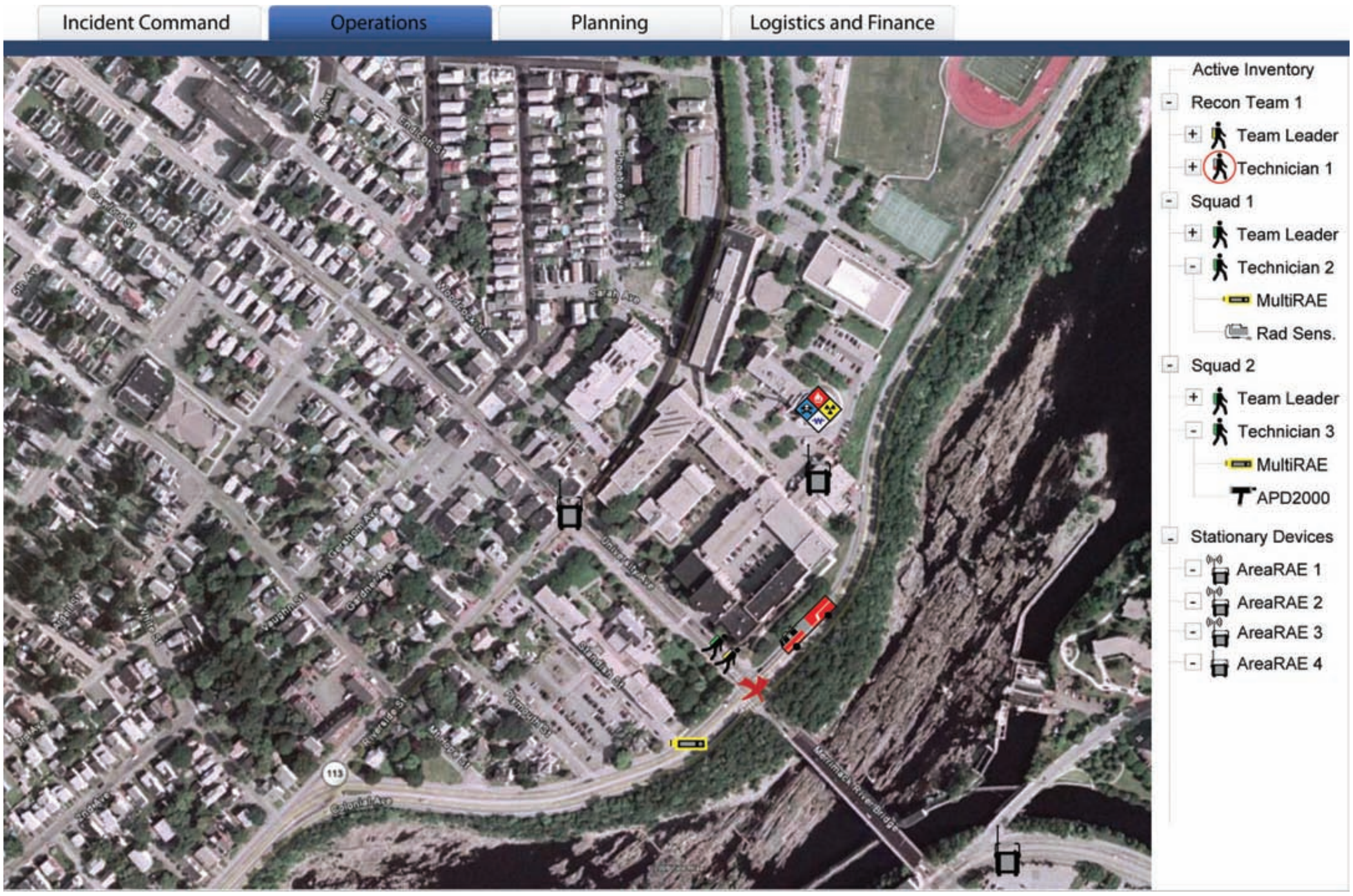


Figure 2. Operations team screen. In addition to the map data, there is a panel showing people, the equipment they are carrying, and unattended equipment. Drilling down on the people will provide additional information, such as the names of the people fulfilling each role and any special information about them.

The subjective assessment used semantic differential questions such as "On a scale of 1 to 6, where 1 means 'many more radio calls' and 6 means 'many fewer radio calls,' do you think using a fully functional version of this system would have any effect on the number of radio calls you would make?" On completion of the test, participants were offered a $50 payment.

Data collection

During the work with the paper prototype, we gave the participants colored pens along with encouragement to draw directly on the prototype. We preserved the resulting marked-up prototype mock-ups.

Participants were instructed to "think aloud" while performing the tasks. The "think-aloud" technique[28] is useful because it allows evaluators to infer participants' assumptions and mental models of how the system works. Evaluators worked in pairs so that one evaluator took notes of the participants' think-aloud comments while the other evaluator tasked and trained the user. We also videotaped each session over the user's shoulder to enable post-test analysis of participants' interaction with the prototype.

In addition to a short demographic questionnaire, the ranking and semantic differential questionnaires completed the data collection effort.

RESULTS

We combined the responses to the interview questions with our observations and participants' verbalizations from the think-aloud technique to produce the following results.

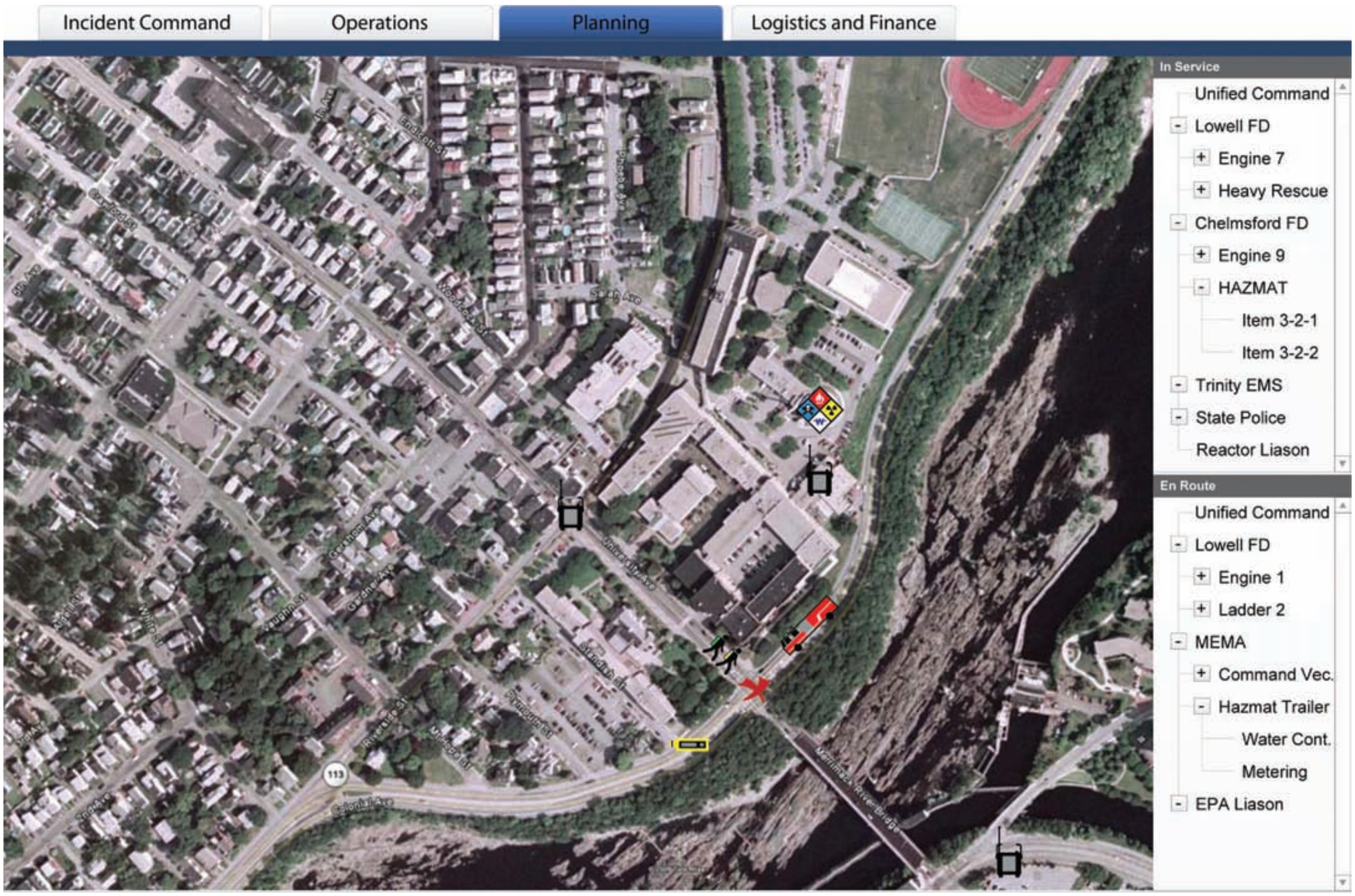


Figure 3. The planning team's screen provides additional detail on resources that are en route or available.

Icons: Alerting and related functionality

Participants provided a few suggested alterations to icons, but most proposed new icons or other symbols that they would like to see on the display, and had general suggestions. One such suggestion, identified by two participants, was to prepopulate the display with known HAZMAT storage areas. One participant suggested an automated means of drawing on the display a circle that is 500 or 1,000 feet in radius centered on a user-designated point; for example, to designate a hot zone. Implementing these suggestions would result in labor and time savings for responders.

During the course of discussing the effect of weather on leaks, four participants stated that they would like to see a plume outlined on the map. Further, the position of the plume should be automatically updated as the wind carried the gas cloud. Two participants would like to see wind and other weather conditions directly represented on the display, and both mentioned that they would like to see this information displayed by default. As weather conditions can greatly impact both the difficulty of HAZMAT response and the procedures used, having this information seems to be very important. If the information is fused with the other data describing the HAZMAT situation, then responders do not have to perform the fusion in their heads (a process that can involve high cognitive workload).

Three participants discussed the desire to have support for evacuation, such as displaying evacuation routes and providing predictions of the numbers of people by location based on the time of day. (Consider a college classroom building, which would be highly populated at 1 PM but be almost empty at 1 AM.) They also wished to see locations of places where people may be concentrated or where they could be sheltered, such as schools or nursing homes, as well as

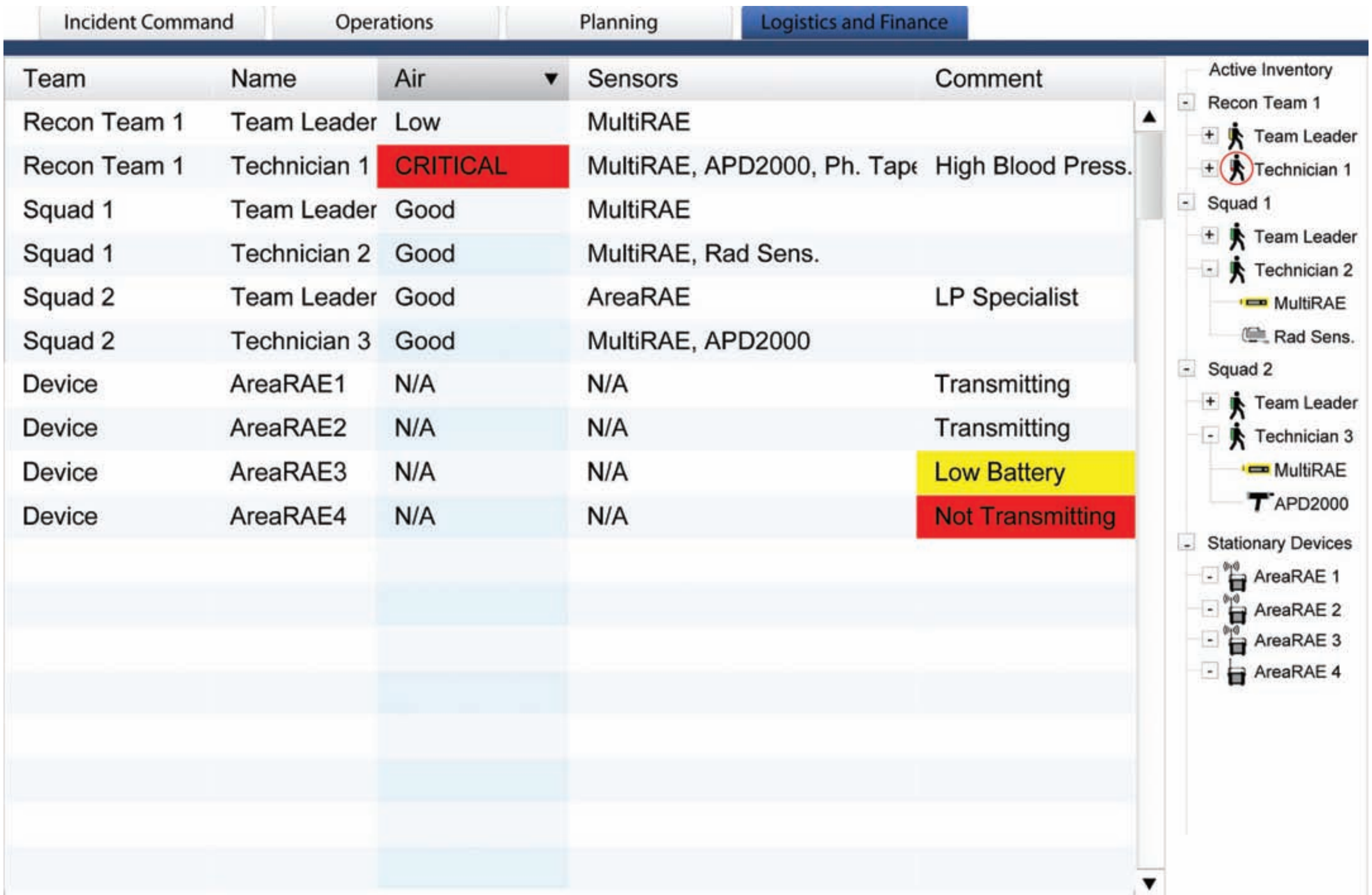


Figure 4. The logistics team's screen shows detailed information on all assets and their status. It can be sorted in various ways, for example, from smallest to largest amount of air available.

symbols to indicate whether an area has been evacuated yet. Having this information could increase efficiency, as it could be easier to manage an evacuation with a clear depiction of the progress of the evacuation and the alternatives for sheltering evacuees.

Three participants discussed alerting in conjunction with icons. One suggested that the icon that indicated an alert for low air should be color-coded completely in green, yellow, or red rather than only having a portion of the symbol colored in this manner. This suggestion is consistent with principles of human-computer interaction, which indicate that larger, brightly colored areas would be easier to see rather than smaller colored areas. Another participant simply noted the necessity for having an alert or alarm for low air. A third participant desired the symbol for a MultiRAE meter to flash when its readings crossed preset thresholds.

Participants mentioned that there should be additional icons for the following: nuclear reactors (using Department of Transportation (DOT) style symbols), liquid propane storage containers, the location of a squad that is assigned damming and diking tasks, a generic HAZMAT placard, police locations, traffic congestion, and snow plows (along with their fuel status, for responses during blizzards).

Maps

Because of the importance of maps to HAZMAT response and the different types of map products that are now readily available, we investigated participants' mapping preferences. Four of the five participants would like to switch among different map types depending on the task at hand. Two of these participants mentioned that satellite maps are useful because they include landmarks that they could recognize and because Environmental Protection Agency liaisons or people on loan from other jurisdictions would not necessarily know what the neighborhood looks like without maps of this type. Satellite maps could thus help familiarize out-of-town personnel by enabling them to do a "virtual walkthrough" of an area. One of the four participants stated that she likes the simplicity of a road map view, but that a 3D view would be helpful to investigate virtually buildings that are taller than normal residences. Another participant values occasional use of 3D maps when he needs to identify the location of the front door of a building. One participant sometimes uses topographical maps to understand the terrain. Finally, the participant who fell into our highest age category prefers to work solely with 2D maps, possibly because only 2D maps were available for much of his career.

Level of detail needed

When asked about the level of detail needed by the IC, three participants said that it is sufficient to have colored dots representing people and objects at the high level, while a fourth said that he needs to know "who's there and their locations." At zoomed-in levels, the participants wanted to see symbols with greater fidelity that can show the type of resource (or person) at a glance and that can list the object's characteristics by touching (selecting) its symbol. For example, touching a person's icon might result in seeing that person's role, name, equipment being worn or carried, and air status. The desire to be able to show details on request for specific persons or objects is consistent with the concept of "focus + context" from human-computer interaction, displaying simultaneously both an overview as well as detailed information on items of interest.[29]

In general, the participants thought that the same default level of detail appropriate for the IC was also appropriate for Operations personnel. Two participants suggested that the IC screen should be designed to include a list representing the location of resources, team members' tasking, and the equipment they are carrying. One participant liked the tree of information so much that he wished it to be difficult to close; he wanted his Operations people to keep it in view at all times. One participant wanted to be sure that he could select individual meters and view their readouts. Two participants would like to know what resources are available at any given moment that would be tailored to the situation at hand. One of these participants also wanted to view the locations of ambulatory rescue and police plus the possible locations of shooters and the locations of those who are wearing weapons in the case of a violent response.

On the planning screen, participants expressed the desire to see as much as details possible regarding the resources and environment. Four participants thought that the information presented on the screens was useful to the operation. Additional comments were suggested, such as what equipment was on scene but staged, whether the Salvation Army and/or Clean Harbors (a HAZMAT clean-up contractor) were on scene, and when additional resources are expected to arrive. In three cases, participants wanted estimated times of arrival for the arriving resources. Another participant thought of the information on the planning screen as being more appropriate for logistics personnel. For planning, this participant wanted to know the HAZMAT that are present, their chemical and physical properties, and—like another participant—recommended actions that he could take (such as what protective devices are appropriate).

When asked about the logistics screen, three participants suggested that this screen should also show resources that are staged and en route. One of these participants added that he would like to know what resources have been requested but are not yet en route. Participants wanted to drill down to the device level to determine the status of the various devices. For example, knowing that an en route vehicle has a decontamination tent on board can be important. One participant would like to select an asset from the list on the screen to highlight its position on the map. A participant voiced the opinion that it is a great idea to track equipment and display it in this manner because "inventory control is a real problem." Finally, one participant liked the idea of showing health issues of responders that should be monitored, such as high blood pressure.

Decision support

One of the most experienced participants suggested several functions that could help responders decide the proper course of action. For example, he suggested having an hour-by-hour history of sensor readings on the planning screen to help him determine if the situation is improving or degrading. In conjunction with investigating chemical properties, he would like to have the system's help in examining the likely consequences of a chemical spill over time under different assumptions as part of performing a time-based "what if?" analysis. He further suggested having a mechanism to ask the system for a recommendation regarding the best course of action. This focus on the possible courses of action is consistent with displaying "decision space" information[30]: information about what can be done, rather than facts about the situation. There was broad consensus among participants that using the system—even as we had prototyped it, without explicit decision support—would help them focus more on problem solving and the associated decision making rather than information gathering.

Information fusion

We have already noted the request to fuse weather and map information, but participants' comments indicated that the desire for information fusion goes much further. Three participants mentioned the benefit of having information that is currently scattered among paper manuals, radio calls, separate computer-based or web-based applications, and in individuals' heads consolidated in one place so that the results could provide a "common visual viewpoint of the status of resources, equipment, and the situation in general" (to quote one of them). A participant mentioned the specific desire to have an electronic, searchable version of the DOT manual incorporated into the system along with a population model.

Concerns

In an effort to ensure that participants would bring up any concerns they would have about such a system, we asked them directly what they did not like about what we had presented. In response, one participant voiced a concern regarding the level of training necessary to use the technology, whereas another participant thought that the technologies would have to "integrate pretty smoothly together." A third participant mentioned the importance of efficiency of use and stated a preference for using voice command rather than typing. One participant suggested having basic and expert modes so that those responders without much familiarity with computers would not feel overwhelmed.

Questionnaire results

We asked six semantic differential questions (questions anchored by opposite words or phrases, such as "difficult" and "easy"). In each case, participants were asked to circle the number that corresponded to their assessment of the question. The questions are given as follows:

If you had this system would you spend much more time maintaining awareness of the situation than what you now do with your current system, or much less time?							
Requires much more time	1	2	3	4	5	6	Saves a lot of time
Do you think there would be any affect on the number of radio calls you would make?							
Many more radio calls	1	2	3	4	5	6	Far fewer radio calls
Please imagine a fully functional system that presented information using the main concepts that you saw in the prototype. Would you characterize this system as:							
Hard to use	1	2	3	4	5	6	Easy to use
Difficult to understand	1	2	3	4	5	6	Easy to understand
No useful functionality	1	2	3	4	5	6	Much useful functionality
No help in maintaining safety	1	2	3	4	5	6	Helpful in maintaining safet

Table 4. Results from semantic differential questions eliciting subjective opinions

Question	Average	SD
Time understanding the situation (1 = more, 6 = less)	4.8	0.50
Effect on number of radio calls (1 = more, 6 = less)	4.4	0.55
Ease of use (1 = difficult, 6 = easy)	4.8	0.84
Ease of understanding (1 = difficult, 6 = easy)	4.8	0.45
Utility of functionality (1 = not useful, 6 = useful)	5.4	0.55
Help in maintaining safety (1 = no help, 6 = helpful)	5.6	0.55

The answers to these questions are summarized in Table 4. The question regarding the likely impact on the number of radio calls earned the lowest average score, 4.4. Several participants made a point of saying that they thought the "content" of the radio calls would be different as a result of having the additional information provided by this hypothetical system rather than the "number" of radio calls being different. The question receiving the highest score pertained to safety. Participants ranked the ability to see low air tanks at a glance and having a visual reminder of alert conditions as very beneficial to safety. All other questions ranged from 4.8 to 5.4, with broad agreement: five of the six questions had standard deviations between 0.45 and 0.55, with only the question regarding ease of use having a standard deviation of 0.84.

We recognized that it would not necessarily be possible to provide a comprehensive set of information to HAZMAT responders in the first functional version of the command and control system, and therefore, we needed a way of prioritizing the information that is most important from the responders' points of view. Accordingly, we asked participants to rank types of information in terms of importance to them. They were given five questions, each with a group of 2-4 items, and asked to assign a "1" to the most important item, "2" to the next most important item, etc, using each number only once. The first question pertained to the importance of tracking detectors, vehicles, and personal protective equipment (such as air bottles). The second question focused on equipment status information regarding batteries, transmission status, detection alerts, and estimated times of arrival for vehicles. The third question concerned three personnel monitoring functions: health (heart rate and body temperature), location, and movement indication. The fourth question compared RFID inventory management for detection equipment versus personnel protective equipment. The fifth question compared the four categories covered by the previous four questions: equipment location tracking, equipment status, people monitoring, and inventory management.

Table 5 summarizes participants' responses. There is broad agreement that personnel protective equipment is the most important type of equipment to track. Similarly, the participants agreed on the greater importance of providing detection alert information versus other types of status information. Participants were likely thinking of alerts regarding personnel safety when they stressed the importance of this type of information. Participants deemed both location and health monitoring to be important. Personnel protective equipment is considered to be more important to manage rather than detection equipment. Finally, of the four categories presented to participants, people monitoring was judged to be most important.

DISCUSSION AND FUTURE WORK

The technology approach that we proposed was rated highly by user test participants for its potential to improve safety and provide useful functionality. The benefits appear to accrue from the combination of technologies being proposed. Having a command and control application that requires its users to enter a lot of data manually would not be useful due to the fast pace of activities in a crisis situation, but having information fed "automatically" to a command and control application has great potential. The combination of GPS to continuously update vehicle-estimated arrival times, RFID tagging to provide up-to-the-minute knowledge of equipment locations, and Sun™

Table 5. Results from ranking questions eliciting perceived order of importance

Ranking choices for each question	Mean rank	Mode rank	Percentage of participants at mode
Q1-Tracking detectors	2	2	60
Q1-Tracking vehicles	3	3	60
Q1-Tracking personal protective equipment	1	1	80
Q2-Battery status	4	4, 2	40
Q2-Transmission status	3	3	60
Q2-Detection alert status	1	1	80
Q2-Vehicle ETA status	2	2, 4	40
Q3-Personnel health monitoring	2	3, 1	40
Q3-Personnel location monitoring	1	1	60
Q3-Movement indication monitoring	3	2	60
Q4-Managing detection equipment	2	2	80
Q4-Managing personal protective equipment	1	1	80
Q5-Equipment location tracking	3	3	60
Q5-Equipment status	2	3	40
Q5-People monitoring	1	1	100
Q5-Inventory management	4	4	80

SPOTs to track whether people have collapsed motionless on the ground paints a rich picture of the situation without any work on the part of the HAZMAT responders.

Although our particular combination of technologies is not the only set that can be proposed, we suggest that researchers keep in mind the principles that we followed when developing our technology vision. We believe that new HAZMAT response technology should be:

- workload neutral (that is, not require additional work on the part of responders),
- inexpensive when deployed in quantity,
- able to undergo decontamination or be so inexpensive that device is disposable (for those assets that are meant to go into the hot zone),
- self-contained; not dependent on fixed infrastructure, and
- available off-the-shelf or with simple modifications.

User testing provided many insights that should also be taken into account when designing new technology for HAZMAT response, especially regarding desired functionality and system characteristics.

As an example of additional functionality, participants wanted plume models incorporated into the map display to see where clouds of toxic gases may drift over time. They also wanted help in planning evacuations, including an estimate of the number of people currently in the vicinity (taking into account the time of day) and the places nearby that they might be brought to such as schools. Further, participants wanted to see weather conditions and forecasts. Participants wanted to be able to play out "what if" scenarios to determine what might happen if they enacted a particular decision. They wanted this system to work seamlessly with the other systems that they used to provide them information about chemical properties.

The test participants would like the system to be very flexible. For example, they would like to be able to use different types of maps (eg, two dimensional and three dimensional; imagery, topographic, and simple road maps). They would like information to be hidden when not needed but be able to drill down to obtain details on objects, such as to determine the equipment that a fire truck is carrying while it is still en route to the scene. They would like to use the system in circumstances beyond that of the usual HAZMAT incident response, such as to know which on-scene personnel are wearing weapons during a violent incident or where snowplows are operating during a blizzard. Participants mentioned that they wanted a version of the interface to operate on a hand-held personal digital assistant device and on a wall-mounted display in a command post.

As we wrapped up each user testing session, the participants often asked us, "so when can we try out a functioning version of this system?" Participants seemed eager to have the capabilities that we are proposing. One person stated, "This could really benefit safety. I rate it highly." He further stressed "this concept is bigger than HAZMAT. I see this system as being beneficial for terrorist incidents, hurricanes, and a lot of different activities . . . for example, showing the location and fuel status of snowplows during a blizzard." Another participant simply said, "This is exactly what we need." All participants felt that the ideas incorporated into the prototype would help them to determine the state of the "big picture" (the overall status of the situation). Without any prompting, four of the five participants volunteered that having this type of system would enable them to have a better idea of the situation and see information more quickly so they could do their jobs more efficiently.

It is the integration and interoperability of each technology that will allow it to adapt to vary workflows and standard operating procedures. We have described many of the physical frameworks that facilitate communication, but researchers will need to develop protocols and application programming interfaces that will allow the devices to "see" and "talk" to each other and adjust their actions and displays appropriately. Many of these protocols already exist and only need to be placed in the context of HAZMAT response. At this point, we believe that all of the pieces to the puzzle exist. The difficult part now is making the interoperability appear seamless to the emergency responders who will use it.

In an enthusiastic endorsement of the use of technology to help HAZMAT responders, a participant stated, "We have to use all the technology that's available. There's nothing worse than getting out there and not getting the information that's needed. This provides the information that I need." He contrasted this approach to the tendency of current operations to transmit all radio verbally over the radios and to proliferate radios as multiple organizations became involved. "I can only listen to so many radios," he said. The description of user needs provided in this article can guide implementation of a command and control system that will bring more of technology's capabilities to HAZMAT response.

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