Identifying Technology Gaps in Hazardous Materials Operations

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Abstract—*Our eventual goal is to design new decision support technologies to enhance understanding of fast-paced, uncertain hazardous materials (HAZMAT) response situations. Before developing improved technologies, we need to understand HAZMAT operations in practice as opposed to how it is presented in the manuals. To gain this understanding, we have been interviewing HAZMAT personnel and observing exercises. This paper presents an analysis of the communications that occurred among personnel, primarily in person or via radio, during three HAZMAT exercises (focusing on one day-long exercise in particular). This analysis allowed us to pinpoint problem areas that could potentially be addressed by decision support technologies. We provide our assessment of technology approaches that could aid the more serious problems we saw in our analysis.*

I. Introduction

Fast-paced group decision-making is challenging, especially in safety critical situations, which are defined as situations "where a run-time error or failure could result in death, injury, loss or property, or environmental harm" [4]. Consider the safety critical domain of hazardous materials (HAZMAT) handling and response. HAZMAT is a mature domain with well-established rules for containment and a nationally recognized training curriculum for handling hazardous materials incidents [6]. Despite the field's maturity and the fact that it is practiced in accordance with the highly regarded Incident Command System [7], members of a Team Leader's Roundtable convened by the International Association of Fire Chiefs Hazardous Materials Committee concluded that "the current response to hazardous materials incidents affords the opportunity for improvement" [5].

HAZMAT response is a prime example of a domain in which teams (which may be formed ad-hoc from the people available) must respond quickly to make safety critical decisions despite incomplete information and, at times, high risk. The goal of our work is to design new decision support technology to enhance the command and control of emergency response situations, using HAZMAT as an exemplar domain. By developing a method to understand and improve information technology support to safety critical operations, we hope to address the more general need identified by the National Research Council, which stated that "disaster management organizations have not fully exploited many of today's [information] technology opportunities" [9]. We have noted an appetite on the part of that community for using technology as evidenced by the statement, "High-tech instruments should be utilized by local HAZMAT teams" [5].

Before introducing improved technologies for HAZMAT incident response, however, we needed to understand HAZMAT operations in practice as opposed to how it is presented in the manuals. In our previous work with other safety critical domains such as command and control (e.g., [11]), urban search and rescue (e.g., [12]), and firefighting (one of the co-authors is a trained firefighter), we have noted that there are always some discrepancies between the procedures as documented in manuals and how operators actually work. In fact, simply asking a person to explain how they perform their job, especially if they are not present in their normal work environment during the explanation, almost always results in a description that is inaccurate to a greater or lesser degree [3].

Related Work

There are commercial products, such as the HazMaster G3 by Pocket Mobility, Inc. [8], that are described as being "decision support systems" (DSSs) for hazardous materials incident response. These systems provide a means of quickly looking up chemicals using their names or, in the case where the chemical is unknown, by its "signs and symptoms." In effect, these palmtop- or laptop-based applications take the place of the paper job aides that HAZMAT personnel have carried ever since HAZMAT became a separate job function. While the current state of the practice is to provide DSSs for individuals making decisions about chemicals, we seek to provide support for groups making decisions at the command and control level.

There have been a few research investigations specifically into command and control for hazardous materials emergency response. For example, Zografos et al. [13] developed a framework for developing DSSs for HAZMAT, which they subsequently used to develop a Hazardous Materials Emergency Response (HAMER) DSS. They used a questionnaire to perform a context analysis, function identification, and task analysis, then surveyed relevant existing and new technologies. Similar to software engineering methods, their functional identification involves specifying input data, processing, and output. The human interface was developed "based on the user requirements and their subsequent transformation into functional specifications, and other special needs revealed during the development phase." What are missing, however, are requirements for information synthesis (as opposed to a simple list of information requirements) and an assessment of the priorities for data presentation and alerting.

Bourne et al. [1] 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 (FALCON). This prototype is aimed towards the individual decision-maker as opposed to aiding a group of collaborators.

Our work is different from these efforts in that they are aimed at more than automating handbooks or providing personal decision-making aids. Instead, we aim to develop approaches for comprehensive command and control tools that synthesize information to help groups make decisions.

II. METHOD

We have interviewed HAZMAT personnel and observed three different exercises. Two of the exercises were training sessions for employees of different companies; these people would already be on site for a HAZMAT situation. Each exercise lasted approximately three hours, starting with a description of the situation by the trainer and moving to a planning session for investigating the problem. At the conclusion of the planning phase, two groups of people were sent into the "hot zone," with a brief exchange of information between the extraction of the first group and insertion of the second. In both of these exercises, there were fewer than 10 people in the training session.

The third exercise was much larger, involving approximately 30 people in a two day training session. The first day was focused on determining what hazards were present in a moving truck that had been involved in a simulated accident. The second day was focused on remediation, which means properly disposing of the hazardous chemicals and making the site safe once again. In order to allow for comparison with the other two smaller exercises, we observed only the first day of this larger exercise.

Because many of the decisions occur after coordination and information sharing, we pay special attention to these collaboration processes. For the longest exercise we observed, we recorded and subsequently transcribed all of the utterances of the exercise leaders and the people with whom they spoke. We made a detailed analysis of the longest exercise and then compared that with the information gathered in the other exercises as a way of checking whether the phenomena observed in the long exercise were also seen in the other exercises. The rest of this section pertains to how we gathered and analyzed the data for the long exercise. When we speak of "the exercise" in the rest of this paper, we are referring to the long exercise.

Our investigation into technology requirements for HAZMAT is informed by the two different information elicitation and analysis techniques. Holtzblatt and Jones [3] developed *contextual inquiry* as a way to observe and interview technology users in their normal environment. Glaser and Strauss [2] developed *grounded theory* as a technique for first obtaining user data and then developing theories that fit the data.

Data collection consisted of three primary sources: voice recordings made of all radio traffic and of two key personnel and all of the conversations that occurred in the vicinity of these personnel; the researchers' handwritten observation notes; and photographs we took of the work environment and work in progress. We transcribed all tapes, resulting in 139 pages from 15.75 hours of recording. We coded the transcripts to characterize the types of conversations participants engaged in and noted especially the points at which a conversation indicated a problem was occurring. Further, we used observation notes made during the exercise to understand the dynamics among the participants and the successes and failures that occurred during the event. We compared our characterization of the training exercise with those we had made of previous events to see whether similar problems occurred.

We discuss the two primary analysis techniques, pulling out themes from observation data and coding tapes to characterize conversations, in more detail below.

Observation Note-Taking

Before the event, we developed guidance for what to capture. As a result, we sketched the physical layout, recorded the official command structure among participants, and noted who was providing some form of leadership independent of rank. We recorded info about the environment (e.g., when it was raining and where generator noise was loudest), noted work pace, task flow, and whether participants were tense or relaxed, energetic or tired. We scattered ourselves throughout the scene and each noted possible unintended deviations from standard operational procedures, any "workarounds" intended to circumvent awkward procedures, actions or situations that seemed to be heading towards safety problems, and any situation that elicited surprise or other strong emotion. We observed which participants collaborated with other participants, the media used (chiefly face-to-face or radio), and the degree of trust that could be seen over the course of the collaborations. We were alert for situations in which people needed additional information to make a decision (and noted what seemed to be missing) and also looked for how participants interacted with technology (e.g., laptops and meters). Finally, we collected work artifacts (e.g., photos that participants took of the hazardous materials scene).

After the event, we pooled our notes and then focused on gaps or problems that we saw. At this point, we entered an iterative process of characterizing problem areas from our observations (which we call pulling out observation themes), understanding problem areas as they emerged from the transcripts, and refining the themes to reflect corroboration from the transcript data. Thus, we used our initial observations as a lens into the transcript to see whether there were other utterances that supported or contradicted the themes, and we refined the themes after coding the transcript (described below).

Characterizing Conversations

The primary purpose of coding the transcripts of the tapes was to help us identify topics of frequent discussion and problems that arose during this training exercise. We used Strauss and Corbin's [10] *open coding* technique from grounded theory: the process by which categories are "discovered" in data.

We defined seven codes (in no particular order), as follows.

1. **Conversations related to documenting or documents**. This code was used whenever exercise participants talked about taking pictures or notes, drawing maps, sketching, writing or recording the setting or situation. We also applied this code when the participants talked about using documentation, referenced documentation, or planned to document something.

Woman: I tried to take as many notes as I could.
Operations Manager [OM]: Okay. And we're gonna actually see if we can pull the pictures up on the computer.
Woman[1]: Yeah, 'cause then that'll help. [Transcript, page 46]

2. **Identifying and obtaining information about materials and hazards.** This code covered discussions of information needed, known, or looked up. The following example is of a case where the exercise participants want to interpret a meter reading regarding ammonia and recall the temperature at which ammonia ignites.

Man: I'm not one hundred percent sure but we'll double check.
Man 2: You know what we should do is…
Man: We'll call ERT, the manufacturer.
Man 2: Well, look in [the] pocket guide and find out what the LEL…you can look up ammonia.
Man: Twenty six percent. It takes twelve hundred and four degrees to set it off-auto ignition. That's what it'll take to make that happen. [Transcript, page 15]

3. **Equipment problems.** This code was always used to describe conversations about malfunctioning or absent equipment. It was also applied to code many situations in which users had problems using the equipment.

Incident Commander [IC]: Didn't you hear us the first time when we said that the body is not there?
OM: Not so good?
Woman: About a third of your transmissions, just judging by the time I was waiting, weren't getting through to me.
OM: Okay.
Woman: So it's radio issues.
OM: Alright. That's not good. [Transcript, page 25]

4. **Spoken communication problems (either face-to-face or via radio)**. This code was applied when there were problems establishing a common understanding of messages communicated verbally, either over the radio or between collocated people. The majority of communication problems were not caused by equipment problems, but instead were caused by failure to follow good radio protocol, by inattention, by inconsistent use of terminology in conversations, or by listener or speaker distraction.

Woman: Right. Well it's, it's right here and the Styrofoam's right next to it with the, one of the lab packs on the groups and then those bags of that crack herbicide…
Man: Lap pack fiber? What do you mean by lap pack?
Woman: Well no, they're just bottles.
Man: Okay.
Woman: Lab bottles. Like liter….what are they liter? Half liter?
Man: Well if they're little then they're probably like a hundred grams or something small… [Transcript, page 62]

[1] When a speaker's identity was unknown, they were denoted as *man* or *woman*. A number notes more than one in a conversation.

5. **Discussions of Procedures.** Conversations coded in this manner include discussions of objectives, protocol, and roles and responsibilities clarification. At many points in the transcript, there were discussions of what needed to happen and who was responsible, often evidencing a lack of clarity. Any time that objectives, procedures, protocols, roles and responsibilities were discussed – in planning, debriefing, or during the entries – we applied this code.

Incident Commander: IC. Understood, over. <not to radio> Do you have your, um… I didn't want to say it on the air, but, uh, I always forget if it's IC or Ops that grants permission for the entry team to enter. As IC I certainly want to know.
OM: Right.
Incident Commander: I think, normally, you are, Ops gives permission.
OM: Yeah I think I call the official time they were able to go in.
Incident Commander: Because Ops runs technical operations.
OM: Okay. [Transcript, page 4]

6. **Safety Critical Events.** We marked any events that we identified as having a safety critical component. We also applied this code to many after-the-fact discussions of, or references to, safety critical events. Many of the events listed under other codes also had a safety critical dimension.

Man: Peroxide test strips. They tested and they got a heavy positive.
Incident Commander: So they should have got out. Now how do you deal with that?
Man: Bomb squad. It's a bomb. I've heard it several and times and that's why C.[name removed for anonymity]*…and I dunno if C. was on a team to go in but he's… 'I'll get, I'll take care of the Acryline.' I dunno what to tell you. You go boom, he goes boom, he goes boom like anyone else.*
Incident Commander: Yeah. [Transcript, page 50]

7. **Monitoring and situation awareness.** This code was used to identify utterances that indicated monitoring the situation, either stating a fact ("ten minutes left on air") or inquiring about the situation ("have you been to medical monitoring yet?").

Woman: Copy. Um, entry team member B.- can we get an air check, um, given your thirty minute bottle?
Team member B: <muffled>
Woman: Entry team member B., could you repeat, please.
Team member B: Yeah, I'm all set. I've got probably 15 minutes left.
Woman: Roger that, thanks. [Transcript p. 182]

Note that we sometimes coded the same excerpt with multiple codes. For example, it is possible to have a safety critical event also pertain to situation awareness. The transcript also had some duplicate conversations when two people who were both wearing microphones talked to each other, but we did not re-code this duplication.

While our transcripts constitute a rich store of data, they have some limitations. We used an excellent recording system but there were still times when words or phrases were unintelligible or provided only part of the communication: gestures to equipment or people sometimes completed the communication but we were not able to capture this non-verbal information. Although we had a subject matter expert on our research team, it was still sometimes difficult to interpret specific terms or phrases, especially if part of the sentence was unintelligible and so we had less context to help in interpretation.

III. Results and Discussion

As described in the method section, we used the coded transcripts to support or motivate modification of our original observation themes. All of the resulting themes are supported by a number of conversations, ranging from a handful to dozens of instances of conversations from the transcripts. Exact numbers are not reliable due to the subjective nature of coding and periods of unintelligibility on the tapes, but what is important to note is that we can point to multiple instances supporting each theme.

Observation Themes

Communications over radios were problematic. Many of the equipment problems we identified (code 3, above) pertained to radios. Even when radios were working correctly, there were many problems establishing a common understanding via radio transmissions (see code 4). For example, participants missed critical radio transmissions, such as one regarding the discovery of a potentially explosive chemical. One team member shared in debrief the impression that as many as one-third of the transmissions did not "get through." They could not always understand the words being spoken (e.g., "bomb" versus "body"). Compounding these problems was inconsistent use of radio protocol (such as acknowledging messages). We observed the same issues in the two shorter exercises.

Equipment was not always trustworthy, especially when affected by lapses in procedure. Besides the radio problems, other equipment did not work as expected (see code 3). For example, a meter did not register a reading because it had a plastic bag placed over it as rain protection. Exercise participants interpreted this null reading as meaning there was no chemical present (which was incorrect). Participants were also unsure which pieces of equipment were in need of decontamination and which were ready to use. They did not have any mechanisms in place to aid them in remembering the location, person responsible, and state of each piece of equipment.

Imprecise communication caused confusion. Even during face-to-face consultations, communications were not always effective (see code 4). Participants in the "hot zone" near the hazards used two different meters and did not make it clear which meter they were reading at any given time, for example. A lack of shared terminology frequently caused misunderstandings, such as the conversation in which there was confusion about the term "lab pack."

Roles and responsibilities were often unclear. Code 5 captured confusion about who was responsible for doing what action at what time. This confusion occurred despite a predefined hierarchy and documented standard operational procedures. We heard utterances such as "who brought the decon brushes?" that indicated uncertainty regarding whose responsibility it was to bring equipment.

The two most urgent types of safety critical incidents (identified with Code 6) pertained to insufficient precautions concerning hazards and not monitoring air supplies closely enough. Two examples stand out. After finding peroxide, the team should have been pulled back immediately but no one responded to the radio transmission concerning its discovery and the hot zone team did not repeat the transmission until getting an acknowledgment. This incident was also identified with Code 2, since they discussed the lower explosive limit (LEL) of a hazardous material. At least one of the hot zone team members was far lower on air than was safe. In the two other exercises we observed, running too low on air also was an issue. In all three exercises, air alarms sounded in the decontamination process, indicating that the air supply was almost depleted.

It was difficult for team leads to maintain awareness (per Code 7) of important characteristics of the environment. The air supply example also illustrates a lack of awareness of this critical resource. Team members did not have cognition aids (either technical or non-technical) to help them get a quick understanding of the critical parameters they need to monitor. Similarly, they don't have a means of quickly obtaining an overall picture of situation status. Sensor equipment brought into the hot zone had telemetry built in, but this capability was not used during the exercise.

Team member performance was uneven. Many team members have little experience with actual hazardous waste situations, although some have considerably more experience. The wide difference in experience and training was reflected in performance, with experienced section chiefs having to repeatedly remind some of the participants to do various tasks. We expected more documentation (Code 1) of where resources were located at any given moment, and we feel this negatively impacted performance. Real-world response teams will likely often contend with a mix of abilities and experience and any procedures or technology that supports them will have to take this fact into account.

Opportunities for New Technology and Improvements

In all three observed exercises, radio communication caused significant problems. The inconsistent use of radio protocols resulted in the loss of critical information. Even with correct radio protocols, the communications were often unintelligible. Improved radios could greatly improve HAZMAT response. Improving the operation of radios is outside of our expertise. Instead, we can offer assistance with situation awareness, decision support, and additional robot borne sensors. Although we cannot per se fix the radios, we might be able to provide redundant information that will be a back up in the case of radio problems.

We observed that some equipment was misplaced during the exercise. Some equipment already has telemetry, but this information was not being used. With this information, equipment could be tracked by commanders and other personnel, avoiding problems of "lost" equipment.

IV. Technology Directions

Although the problems that we observed were very specific in nature, a need emerged related to awareness of asset locations. The location of people going into the hot zone and the location of key command personnel is an example of human assets needing to be tracked. Gas meters, self contained breathing apparatus (SCBA) bottles, and testing systems are examples of equipment assets needing to be geo-located. In a large-scale response, the location of vehicles and the resources within those vehicles are examples of hybrid or compound assets that need to be tracked. The command personnel rely on detailed awareness of the locations and availability of these elements to effectively plan their operation and optimize mission success.

A second need pertained to continually monitoring the status of the above mentioned assets, which is currently done manually. The medical and safety personnel are tasked with ensuring that all of the humans involved in the response are within safe limits for heart rate, blood pressure, body temperature, hydration, and ambient temperature, just to name a few parameters. Self-contained breathing apparatus (SCBA) have a finite amount of air and people will use this air at different rates depending on their cardiovascular capabilities. Equipment such as the gas meters, radiological sensors, and testing equipment may be constantly generating data about the atmosphere and unseen hazards. Finally, adequate levels of fuel for hybrid assets such as fire trucks and generators are pre-requisites to a successful mission.

We believe that both of these command and control needs can be immediately mitigated through the use of commercial off the shelf (COTS) technology at a reasonable cost to the responder community. Technology exists to passively monitor vital health information of every person that will be physically tasked during the deployment. If personnel were simply tagged with global positioning system (GPS) receivers and low-range transmitters, the location of the assets within the disaster site could be monitored and recorded. The use of radio frequency identification (RFID) tagging by logistics personnel on site could accurately monitor the use and replenishment of equipment assets such as air meters and SCBA bottles. Metering devices could also be fitted with low-power transmitters that allow for active monitoring of the data collected from these sensors.

With the position and data collection infrastructure in place, we focus on managing the data flow to the command and control personnel. Traditionally, location information is provided with paper maps and radio communication. Recent developments in multi-touch table-based display technology can provide a "bridge" between more traditional methods and digital data collection. Location, health status, and equipment status could be displayed on the "digital map" to inform the command staff and lessen the need for the radio communication that would have otherwise provided this information with lesser fidelity. A table-based digital map display would have several advantages. It is more visible to groups of people; tables are a natural focal point for collaboration; and there is a natural analog between spreading out paper maps on a horizontal surface and orienting computer-based maps on a table-based display.

As the ubiquity of touch table technology increases, we fully expect to exploit its versatility and direct analogy to paper-based information resources. It is only through the careful and direct analysis of actual operations that we can ensure the right information is presented to the right people, at the right time, and in the right format while lessening the need for direct verbal (and potentially misunderstood) communications. All of the pieces are technologically mature. It is now a matter of tightly coupled user design and task-oriented implementation.

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