Human-Robot Interaction in USAR Technical Search: Two Heads Are Better Than One

J.L. Burke & R.R. Murphy
CENTER FOR ROBOT-ASSISTED SEARCH AND RESCUE
University of South Florida
4202 E. Fowler Avenue, ENB 342
Tampa FL, 33620, UNITED STATES
E-mail jlburke4@csee.usf.edu

Abstract

Effective human-robot interaction in Urban Search and Rescue robotics currently requires a minimum 2:1 human-to-robot ratio. The demands are not just physical (though the task at present is facilitated by having a second person assist with physical robot operations); cognitive challenges are presented by the key-hole effect, teleproprioception and telekinesthesis. In studies with 2:1 robot teams, operators who talked more with their teammates about the search environment, the robot's situatedness in that environment, and search strategies seemed to develop a shared mental model of both the search environment and the task at hand. Moreover, operators who talked more about goal-directed aspects of the search task with their teammates were rated as having better situation awareness and task performance. Effective teams were nine times more likely to find victims in search exercises. This suggests that robot-assisted search and rescue is a team task and good human-robot interaction is critical to performance.

1. INTRODUCTION

Much of the literature on human-robot teams is predicated on the assumption that a single person will be able to control or supervise multiple robots. Indeed, many research projects-in-progress propose a one-to-one human-robot ratio as an accepted setpoint; few are looking to see if a single person can really operate a single robot effectively in a given task or environment. Because of the rather traditional viewpoint that robots will do the dirty, dull or dangerous work [1], robots tend to be perceived as mindless, obedient entities that will go and do as commanded with a minimum of attention or effort required from their human taskmasters. In reality, this is proving *not* to be the case. The Global Hawk unmanned aerial vehicle in use by the United States for missions in the Middle East requires a minimum of two operators, despite the high degree of onboard navigation [2]. The Mars Rovers, one of the most successful human-robot team efforts, currently keep a staff of hundreds employed for their mission on Mars [3]. These robots, granted, have high level capabilities and some degree of autonomy, making their cases rather special; surely a simpler robot (e.g., one requiring teleoperation) could be operated by one person—or so one would think.

Field studies of mobile robots for urban search and rescue in highly realistic training exercises refute this assumption. While only one person can drive the robot at a time, both people are required to look. In this paper, data is summarized from two field studies with rescue robot operators that strongly suggest a minimum 2:1 human-to-robot ratio is required for effective robot-assisted technical search in Urban Search and Rescue (USAR) environments. These results are expected to apply to other applications, e.g. medical, military and service robotics.

Urban search and rescue involves the rescue of victims from the collapse of a man-made structure. Physically the environment is unstable and dangerous, consisting of piles of concrete rubble, exposed metal, dust and debris; hazardous materials or gases may be present. Used for the first time in the aftermath of the World Trade Center disaster, small mobile robots offer a valuable contribution to search and rescue efforts in this difficult environment in that they can go into places deemed too small or unsafe for people or dogs. Robots involved in search and rescue operations must team with people both physically (the robots must be backpacked in to the search areas and are tethered while in use) as well as perceptually and cognitively (people interpret the video, audio, and sensor data provided by the robots and make decisions regarding their actions and those of the robots accordingly). The robots' small stature and resulting point of view exacerbates a keyhole effect, i.e. the limited angular view associated with many remote vision platforms that gives remote observers a sense of trying to understand the environment through a peephole [4]. Moreover, the robots are often used to search confined spaces normally considered unreachable, so that the operator has no prior mental model of the potential search space. Operators are required to work in extreme conditions, and are subject to cognitive and physical fatigue. Consequently, human-robot interaction in USAR presents challenges in teleproprioception and telekinesthesis [5]. The findings presented in this paper from two field studies with rescue robot operators indicate a minimum 2:1 human-to-robot ratio is needed to address these challenges.

The remainder of this paper is organized as follows: Section 2 presents related work, focusing particularly on prior field research in rescue robotics. In Section 3, the field research methodology used in the two studies is described. Section 4 presents three key findings from these studies pertaining to shared mental models, goal-directed communication and the interaction between team communication, situation awareness and team performance. Lastly, conclusions and recommendations appear in Section 5.

2. RELATED WORK

Human-robot interaction is a field in its infancy [6]; subsequently the body of literature is small and encompasses a variety of applications and approaches, e.g. [7] – [9]; we narrow our focus to the field domain of rescue robotics [10] – [15].

Challenging aspects of human-robot interaction in USAR are situation awareness, perception and communication. In July, 2001 Casper & Murphy [10] conducted an ethnographic study of Florida Task Force 3 members using robots to search for a victim (a fireman-down scenario in a partially collapsed building). The study showed that technical search task activities sometimes overloaded the operator and posited that a second person might be needed to assist the operator interpret multiple sensor data while navigating, as Woods suggested in [12]. Casper and Murphy's [11] analysis of video data collected during the World Trade Center disaster response highlighted a variety of human-robot interaction issues. The limited sensor capabilities of the robots forced the operators to rely solely on the visual image provided through the robot's eye view; the lack of expected perceptual cues and operator cognitive fatigue also contributed to operators' difficulties. Casper & Murphy [11] also noted that communication of robot information extends beyond the operator and his immediate teammates to include others with heterogeneous goals and interests, a point reiterated in [13]. The findings from these earlier field studies spurred the research presented here, which focuses on situation awareness and team processes.

3. FIELD RESEARCH METHODOLOGY

Based on the observations noted in the previous section, field studies [14], [15] were conducted to explore the criticality of situation awareness in robot-assisted search and rescue, using Endsley's three-level model, which defines situation awareness as "…the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future" [16]. A second goal was to examine the effects of introducing a new technology (the robot) into an established team-based work environment (USAR) through analysis of team processes and communication. Procedures for data collection and analysis are outlined below.

Setting, Participants and Apparatus. The two field studies from which these findings are taken were conducted during high fidelity disaster response training exercises conducted annually by professional USAR instructors in varying locations. These training exercises consist of 2-3 days of intensive classroom and hands-on training followed by a 24-hour deployment evolution on an actual collapse site. These sites are not simplified, and present the same physical hazards and conditions as encountered during an actual disaster response. Mannequins are placed in various locations within the collapse site to provide responders with experience in search and rescue operations**.** Study participants (n = 33) are experienced firefighters seeking USAR certification. The Inuktun Micro Variable Geometry Tracked Vehicle (see Figure 1) is used in all but one of the 33 operator runs across the two field studies (one operator in the first study used the similar Inuktun Microtracs robot). The VGTV is a polymorphic robot which can change from a flat position to a raised, triangular position. The Inuktun robots have limited communication capability; the user interface offers little information beyond a visual view of the environment from the robot's camera. The operator is given basic control capability: traversal, power, camera tilt, focus, illumination, and height change for the polymorphic robot.

Data Collection & Analysis Procedures. Our method of data collection is a modified version of the procedure used in [10]. Two cameras simultaneously record the view through the robot's camera (what it sees) and a view of the operator and the Operator Control Unit (what the operator is seeing and doing.) When the robot is visible, a third video unit records an external view of the robot in use.

The videotaped data is then edited and coded using behavioral analysis software. Views of the operator and robot appear side-by-side, allowing trained raters to code statements made by both the operators and surrounding personnel.

Figure 1. Robot system used in field studies.

Measures. The Robot-Assisted Search and Rescue Communication Coding Scheme (RASAR-CCS) is designed to examine USAR robot operator interactions with team members and to capture indicators of robot operator situational awareness. Trained raters code each statement on four categories: 1) speaker-recipient dyad, 2) form, 3) function, and 4) content of the communication. A detailed description of the Robot-Assisted Search and Rescue Communication Coding Scheme can be found in [14]. Raters also provide an overall assessment of each robot operator's task performance and situation awareness, using a 5-point Likert scale (1=low, 5=high).

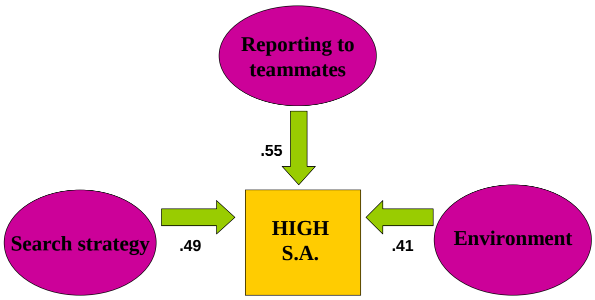
4. FINDINGS FROM THE FIELD

The purpose of this paper is to make the case that robot-assisted technical search is a team task, requiring a minimum 2:1 human-to-robot ratio. Three major findings from two field studies involving 33 robot operators are presented in support of this claim: first, that the task involves *development of a shared mental model* between the robot operator and his or her teammates; second, that the *quality of team communication* (goal-directed vs. not) is more important than quantity in terms of development of this shared mental model; and last, that *team performance is enhanced* when team members create shared mental models of the search space by talking about goal-salient aspects of the task. Detailed support for these findings is provided [14], [15] in the form of frequencies & percentages of operator statement types, correlational analyses of operator statement categories, and chi-square analyses of groups of operators rated as having high or low situation awareness. In addition, a job-relevant task performance outcome (victim location) provides compelling evidence that effective team processes are positively related to robot operator performance.

4. 1 Shared Mental Models

Robot-assisted technical search requires two heads *thinking*, not just two bodies physically working with the robot. Operators had great difficulty building and maintaining situation awareness (SA) during the search task. Over half of their statements in [14] were related to gathering information about the environment and the robot; in [15], nearly two-thirds (63%) of operators' statements were SA-related. To compensate for their difficulties, operators worked with teammates to create shared mental models of the search space. Operators talked to their teammates about the environment and the robot's situatedness in that environment. Furthermore, operators' statements to teammates articulated *information synthesis*, i.e. they related what they were seeing through the robot to things they had seen before (or had prior knowledge of). This result suggests operators were attempting to develop a shared mental model with teammates to increase situation awareness. They also used this information to plan and devise search strategies. Correlational analyses of operator-to-teammate statements depict the team-oriented nature of the robot search task. Results suggest that instructions given by the operator were significantly related to search strategy, the environment and information synthesis; moreover, instruction statements made by operators correlated significantly with planning statements. Importantly, our results show that *reporting* what they were seeing to teammates and *planning* were closely related; operators were using what they were seeing through the robot's eye to form a mental model of the search space (and the robot's position in that space) in order to devise search strategies. Planning not only facilitates the building of shared mental models with teammates, it can also result in improved team performance [17]. Operators in [15] who engaged in more reporting to teammates, especially about the environment and search strategies, were rated as having better situation awareness (Figure 2).

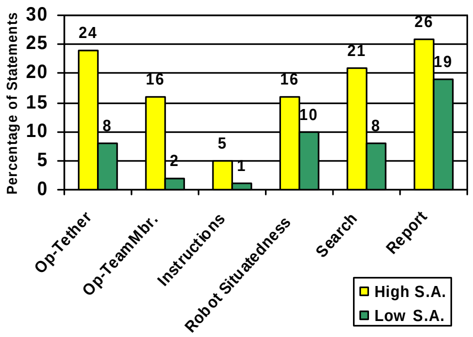
Figure 2. Links to operator situation awareness.



4.2 Goal-directed communication

Higher levels of SA in robot operators depends more on the *quality* of the communications between robot operator and teammates than the quantity of communications. Operators who talked about goal-directed aspects of the task were more cognizant of the search environment and the robot's situatedness in that environment, as evidenced by their higher situation awareness (SA) ratings. As mentioned previously, trained raters provided global assessments of SA for each operator (5-point scale; 1=low, 5=high). These ratings were used to identify operators with high versus low situation awareness in [14] and [15]. Data from operators receiving ratings of 1-3 were combined to form a Low SA group; similarly, data from operators receiving ratings of 4-5 were combined to form a High SA group. Chi-square analyses were used to examine differences in High and Low SA operators relative to *whom* the operator was communicating with, *what* they were saying, and *why*. The results of these analyses (reported in [14] and [15]) offer support for the influence of team behaviors on situation awareness. As shown in Figure 3, operators who talked more with other team members received better SA ratings [14]. High SA operators also engaged in higher levels of reporting, i.e. they talked more to their teammates about situation awareness-related factors in the search environment. It would seem that talking with one's teammates about the situation helps create a shared mental model of what's happening.

Figure 3. Significant statement percentages for high & low S.A. operators in [14]: who, what & why?



In contrast to the first study, however, chi-square analyses of high SA and low SA operators in [15] (Figure 4) revealed that operators with better situation awareness talked more to the group as a whole rather than to a specific team member. Low SA operators not only talked more to their teammates, but also received more incoming communication from team members and tether managers. These findings suggest that mere frequency of communication with the tether manager and other teammates does not increase the operator's situation awareness; rather, it is the nature and quality of the communication. Operators with better SA made significantly more comments and observations about search strategy, the environment and the robot's situatedness in the environment (see Figure 5); in contrast, low SA operators asked more questions. Overall, operators rated as having good situation awareness in [14] and [15] engaged in more reporting about the robot and the environment than low SA operators, i.e. they talked more about situation awareness-related factors in the search environment. These findings suggest that high SA operators were more focused on goal-directed cues. In [15] they also made more statements related to planning (Figure 6). Operators with low SA did not seem to have a plan as to how to search using the robot. A significantly larger number of statements seeking information or confirmation were made by operators with poor SA — seemingly an indication of their lack of a clear mental model of the robot-assisted search task. Talking about the situation can help create a shared mental model of what's happening. It seems, however, that high SA operators are talking more about goal-directed salient aspects of the task.

Figure 4. Significant percentages for high & low S.A. operators in [15]: who did they talk to?

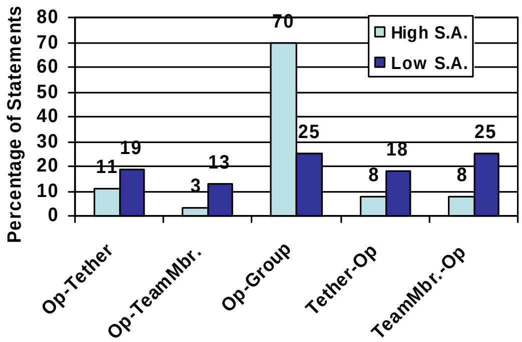


Figure 5. Significant percentages for high & low S.A. operators in [15]: what did they say?

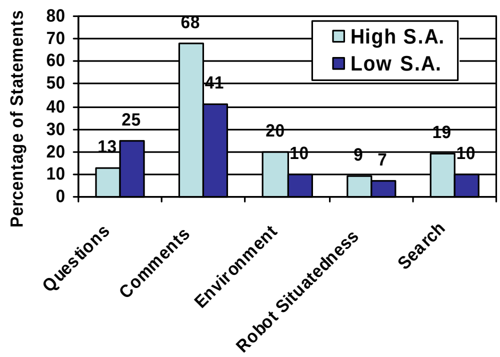
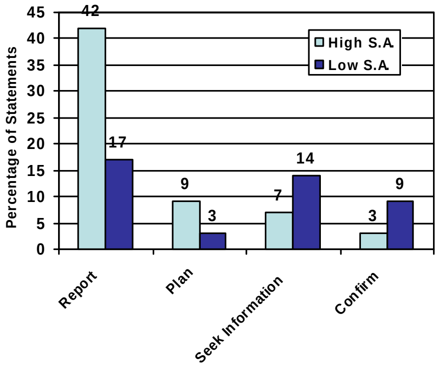


Figure 6. Significant percentages for high & low S.A. operators in [15]: why did they say it?



The differences in team member roles over the two studies highlight the importance of shared (team) mental models. In the first study, when a third team member was present, he or she was invested in the search role, looking over the operator's shoulder and assisting in the search process. By contrast, the second study was designed for pairs of operators working together. When a third team member showed up, it was strictly as an observer, or bystander, and seemed to distract operators overall. The data from [15] suggests that having a third team member participate in the task may actually contribute to a decrease in the operator's level of situation awareness if the team member has no goal-directed role. It remains to be seen, however, whether having a third team member involved in the search task is necessarily a hindrance. Further research should examine the relationship between the number of problem-holders and various situation awareness and performance outcomes. Research investigating role allocation among team members and dynamic role-switching is also needed.

4.3 Communication, SA & Performance

Operators in high-functioning teams (i.e. teams who create shared mental models of the search space and talk about goal-salient aspects of the task) are 9 times more likely to locate a victim [15]. Task performance ratings (successful victim location) were gathered for 16 participants; 82% of the high SA operators successfully located the victim mannequin, while only 60% of the low SA operators did so (Figure 7).

Figure 7. Task performance results (victim found) for robot operators.

Operators	found	not found	Total
High SA	9	2	11
Low SA	3	2	5
Total	12	4	16
Total %	75%	25%	100%

The odds-ratio (comparing the odds of a high SA operator locating the victim to the odds of a low SA operator locating the victim) in this study is 9:1, meaning an operator with good situation awareness is 9 times more likely to successfully locate the victim than an operator with poor SA. The mean number of hours into the exercise, however, was less for high situation awareness operators (M=11.4) then for low situation awareness operators (M=14.3). Therefore, fatigue was very likely a factor. One cannot discount the effects of time and fatigue on the operators, as evidenced in [15] by the differences between those who participated in the experiment earlier in the response and those who participated toward the end. These effects, however, are actually important to our understanding of human-robot interaction in this domain, and therefore should not be controlled (even if we could).

Because the mapping between SA rating and task performance in [15] was not absolute, i.e. there were some high SA operators who did not find the victim, and some low SA operators who did, we went back and looked at the videotapes to look for factors that may have contributed. For 3 of the 4 operators who did not find the victim, the human:robot ratio was 3:1 rather than 2:1. This again suggests a third team member may have been a distraction. Looking at the three operators who were rated as having low SA, yet found the victim, we noticed that two of the three had a lot of help and instruction: one from the tether manager who had just completed the first part of the search, and the other from a team member who basically took over the role of problem-holder (and may have completed the search himself earlier in the evening). The third operator may have been distracted by the researcher; he also was making a lot of jokes (off-task) while the victim was in view. He actually had the victim in sight for several minutes before identifying him.

Looking at two operators who were rated as having high SA, yet did not find the victim, one operator simply went right by the kitchen (where the mannequin was located) without the opening ever coming into view. He conducted a very thorough search of every other room, identifying them and describing structural details. Though he carefully named each room (bathroom, closet, bedroom), he never mentioned the existence of a kitchen or the need to search for one. This highlights the cognitive fatigue that is a factor in any USAR operation. The other operator did stop and look into the kitchen, but was far enough away from the entrance that he evidently could not distinguish the human figure in the floor, though he did remark on the presence of the kitchen cabinets (which is where the mannequin was located!) These critical incidents of human error again highlight the need for perceptual assistance and cognitive augmentation.

5. SUMMARY & RECOMMENDATIONS

Robot-assisted technical search in USAR is a challenging task, overloading the operator not only physically, but cognitively and perceptually. Therefore, a minimum 2:1 human-to-robot ratio is required. Three major findings from two field studies involving 33 robot operators are presented in support of this claim: first, that robot-assisted technical search requires two heads *thinking*, not just two bodies physically working with the robot; second, that the *quality* of team communication (goal-directed vs. not) is more important than quantity in terms of development of a shared mental model; and last, that teams who create shared mental models of the search space by talking about goal-salient aspects of the task are 9 times more likely to perform effectively. Support for each of these findings is summarized here, with detailed results in the form of frequencies & percentages of operator statement types, correlational analyses of operator statement categories, and chi-square analyses of groups of operators rated as having high or low situation awareness reported in [14] and [15]. In addition, a job-relevant task performance outcome (victim location) provides compelling evidence that effective team processes are positively related to robot operator performance.

Based upon these findings, the following recommendations are made:

1) The operator's mental model of the search environment is enhanced by voicing goal-salient observations: being able to "back up" the robot's video might help in confirming/correcting mental models of the search space.

2) Team mental models may be enhanced by identification/clarification of the roles and activities involved in robot-assisted search. If a third team member is available to participate in search, she must be attuned to the goals/nature of the task and respond accordingly; i.e., help the operator determine what is salient through the visual channel and develop search strategy by listening and observing, but limiting her involvement to that role (no driving, no joking around). This has implications for training and performance evaluation of future robot operators in USAR; establishing a list of roles, tasks and activities for robot-assisted search and rescue is clearly a process that will go through several iterations as new advances are made in robotics technology, and new uses are discovered for rescue robots in USAR.

References

[1] R.R. Murphy, *Introduction to AI Robotics*. Cambridge, MA, MIT Press, 2000.
[2] F. Colucci, "Air Force Refines Training Programs for UAV Operators", *National Defense Magazine*, May 2004.
[3] Retrieved from http://marsrovers.jpl.nasa.gov/people/ on May 31, 2004.
[4] D. D. Woods and N. Sarter, *Cognitive Engineering in the Aviation Domain*. Hillsdale, NJ: Erlbaum, 2000, ch. Learning from Automation Surprises and Going Sour Accidents.
[5] T.B. Sheridan, *Telerobotics, automation, and human supervisory control*. Cambridge, MA, MIT Press, 2000.
[6] J. Burke, R. R. Murphy, E. Rogers, V. J. Lumelsky, and J. Scholtz, "Final report for the DARPA/NSF interdisciplinary study on human–robot interaction," *IEEE Trans. Syst., Man, Cybern. C*, vol. 34, pp. 103–112, May 2004.
[7] Khatib, O., Yokoi, K., Brock, O., Chang, K. & Cas al, A. (1999). Robots in human environments: Basic aut onomous capabilities. *International Journal of Robotics Research*, *18*(7), 684-696.
[8] C. Breazeal, *Designing Sociable Robots*. Cambridge, MA: MIT Press, 2002.
[9] R. Ambrose, H. Aldridge, R. Askew, R. Burridge, W. Bluethmann, M. Diftler, C. Lovchik, D. Magruder, and F. Rehnmark, "Robonaut: Nasa's space humanoid," *IEEE Intell. Syst.*, vol. 15, no. 4, pp. 57–63, 2000.
[10] J. Casper and R. Murphy, "Workflow study on human-robot interaction in usar," in *Proc. Int. Conf. Robotics Automation*, 2002, pp. 1997–2003.
[11] J. Casper and R. Murphy, "Human-robot interaction during the robot-assisted urban search and rescue effort at the world trade center," *IEEE Trans. Syst. Man, Cybern. B*, vol. 33, pp. 367–385, June 2003.
[12] D.Woods, J. Tittle, M. Feil & A. Roesler, "Envisioning human-robot coordination in future operations" *IEEE Transactions on Systems, Man & Cybernetics: Part C: Special Issue on Human-Robot Interaction*, vol.34, pp. 210-218.
[13] R.R. Murphy,"Human–robot interaction in rescue robotics", *IEEE Transactions on Systems, Man and Cybernetics C*, vol. 34, pp. 138 – 153, May 2004.
[14] J. Burke, R. Murphy, M. Coovert, and D. Riddle, "Moonlight in Miami: An ethnographic study of human-robot interaction in USAR," *Human-Computer Interaction, Special Issue on Human-Robot Interaction*, vol. 1, 2004, to be published.
[15] J. Burke & R. R. Murphy. "Technical report on Bridgeport, CT field operations, October, 2002". *CRASAR-TR 2004-17*.
[16] Endsley, M. (1988). Design and evaluation for situation awareness enhancement. In *Proceedings of the Human Factors Society 32nd Annual Meeting, 1*, (pp. 97-101). Santa Monica, CA: Human Factors Society.
[17] Stout, R., Cannon-Bowers, J., Salas, E. & Milanovich, D. (1999). Planning, shared mental models, and coordinated performance: An empirical link is established. *Human Factors, 41*(1), 61-71.