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Workflow Study on Human-Robot Interaction in USAR

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Abstract— **This paper presents findings from field trials observing human-robot interaction between certified rescue workers and two types of tactical mobile robots at a rescue training site. Data was collected on how members of a fire rescue department directed the use of two types of robots for four tasks (climbing stairs to investigate condition of upper floors, searching dark, cluttered environments with two different sensor suites, and exploring vertical voids). The prototypical workflow, the type and frequency of errors during each task, how the robot workflow compared with existing USAR practices, and any additional information that came out during debriefing is reported for each task. Two major workflow patterns that could be partially or fully automated were identified: *stairwell search* and *topological search*. In addition, *collaborative teleoperation* appeared to be an important multi-robot strategy. Rescue workers rated the robots' performance superior to existing methods for searching and for exploring vertical voids, but not for stairwells.**

Keywords— **Urban Search and Rescue, mobile robots, human-robot interaction.**

I. Introduction

Mobile robots have been proposed as a valuable addition to Urban Search and Rescue (USAR) efforts. This paper reports on a study characterizing how such robots were used by rescue workers through direct observation of certified rescue workers interacting with prototype robots during rescue training and contrasting theses interactions with existing USAR practices. Robots had not been fielded in a real disaster prior to the September 11th terrorist attack and their use has not been codified by disaster management agencies such as the Federal Emergency Management Agency (FEMA) in the USA. Therefore, describing existing USAR practices, characterizing how robots are likely to be used (e.g., workflow analysis), and identifying how rescuers want to interact with mobile robots (e.g., human-robot interaction) are fundamental contributions to this emerging domain.

In order to collect human-robot interaction (HRI) data, a preliminary field test was conducted on July 6, 2001, in Tampa, Florida, with the Hillsborough County Fire Rescue Department (HCFRD). Three mobile robots (an RWI Urban, an Inuktun MicroVGTV, and an Inuktun MicroTracs) were fielded under the direction of fire rescue professionals during a rescue training session. The findings contribute a set of scripts that are candidates for automation, an evaluation of the types of errors that occur in the field, a better understanding of existing practices in USAR and where intelligent robots can be used, and a data collection methodology.

The paper is organized as follows. It first discusses the relatively sparse related work in USAR robotics and describes the general field test setup. Next, it details the four tasks given to the robots by the rescue workers, the observed workflow, frequency and types of errors encountered, and assessments of the technology by the rescue workers. The conclusions make recommendations for the next steps in creating intelligent USAR robots.

II. Related Work

An overview of USAR as a robotic domain can be found in [9] or [2]. Work in robotics for USAR has concentrated on either platform development (most notably [3], [4], [6], [11]) or software development (see [1], [5], [8]). While some efforts have considered the role of the human as part of the robot team for USAR, especially [1], [7], [10], it does not appear that human-robot interactions for USAR have been formally characterized.

III. Field Tests

The basic test was intended to simulate the insertion of robots into a real disaster team. The USF team arrived with the robots and immediately reported to the rescue director, called the Incident Commander (IC). The IC then directed the team where to set up the staging area for the robots, and tasked the robots. All activities were recorded on videotape. The robots were teleoperated in order to avoid any concerns over whether any autonomous components would distract or bias the rescue workers. Essentially, the robots were a blank slate for the rescue workers.

A. Location and Personnel

The field test was conducted with certified rescue members of the HCFRD under the direction of Special Operations Chief Ron Rogers. The field environment was an old evacuated four story office building in

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downtown Tampa used for fire training courses. The fourth floor was partially destroyed and littered with building material rubble to simulate rescue of victims or downed firemen in realistic situations. The HCFR department had set aside the day for training with robots and attempted to provide the most realistic situations possible. Additional observers from the news media were present but did not interfere with data collection.

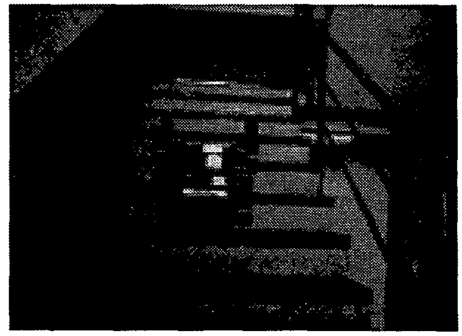
The field test began on July 6, 2001, at 7:50AM and ended at 2:10PM. The average outdoor temperature was 94 degrees Fahrenheit, with temperatures considerably higher inside the unventilated building. Two main stairwells and an operational elevator provided access to each of the four floors. AC power was available in most areas. All major furniture items had been cleared out. Walls had been torn apart. Ceiling debris and wiring cluttered walkways. The first floor was used primarily for staging equipment. The third and fourth floors were the "hot zones" for the tasks described below. The lights were off in the building and the fourth floor was totally dark with emergency strobe lighting active. Blueprints or layout information of the building were not available.

B. Equipment

Three tracked robots were used for data collection: an RWI Urban, an Inuktun MicroVGTV, and an Inuktun MicroTracs. The Urban was run in two different configurations, with and without a forward-looking Indigo Alpha infrared camera (FLIR). Table I summarizes the major characteristics of each robot.

The Urban, shown in Fig. 1a, is a prototype robot developed for the Defense Advance Research Projects Agency for tactical mobile robot applications, including USAR[7]. It is both small and agile, having a footprint of 62 by 50 cm, and polymorphic or shape-shifting capabilities allowing it to climb stairs or rubble and to elevate the main compartment and sensor suite (similar to a small animal standing on its hind legs). The basic Urban sensor suite consists of thirteen sonar sensors, video, magnetic compass, and a tilt sensor. A FLIR can be added. The Urban has an on-board 240MHz Intel based motherboard with 64MB of RAM and uses wireless Ethernet to interface to an Operator Control Unit (OCU).

The Inuktun MicroVGTV and MicroTracs robots, shown in Fig. 1b, are equipped with a color CCD camera on a tilt unit. Power, video, sound, and control are provided via a tether. The MicroVGTV is a polymorphic robot capable of lifting the camera up to a higher vantage point. Neither has on-board computing power. The MicroTracs System is not polymorphic but has bi-directional audio.



a.

b.

Fig. 1. Views of robots: a) an Urban and b) the MicroVGTV (left) and MicroTracs (right).

C. Data Collection

The HCFR department asked to evaluate the robots in four tasks:
1. climb stairs to investigate the condition of upper floors,
2. search a dark and cluttered floor for a downed fireman (simulated by a dummy dressed in complete fireman bunker gear),
3. search a dark and cluttered floor for a downed victim using FLIR (simulated by a person pretending to be unconscious), and
4. explore a floor by entering from a hole in the ceiling.

For each task, a notebook of observations was kept and video and audio data recorded from four synchronized camcorders. Each camcorder was hand-held by a student volunteer who attempted to optimize both the visual and audio recording for their designated target. The targets for each camcorder were: the operator and the control unit being used, the robot in action, the IC and other HCFR department members within the vicinity of the operator, and miscellaneous views, such as a second robot or control station in action. Before each task, the IC was asked to verbally explain why he was giving each command. After each task, the IC, operator, and the Special Operations Chief were de-

TABLE I
COMPARISON OF THE ATTRIBUTES AND SENSORS OF EACH ROBOT.

Attribute	Urban	MicroVGTV	MicroTracs
CPU	Pentium	none	none
Comms	wireless	tether	tether
Power	battery	tether	tether

Sensors	Urban	MicroVGTV	MicroTracs
Video	CCD FLIR	CCD	CCD
Audio	none	none	2-way
Range	sonar	none	none

briefed and asked to comment and make suggestions for more desirable sensors, hardware, and software.

In addition to the video recordings, observers kept track of errors or hardware failures. Observed errors were divided into two categories: *navigational* and *communication*. Following the taxonomy, the three types of navigational errors were further subdivided into course corrections, collisions, and pose errors.

IV. RESULTS

Results of the four tasks are summarized below in separate subsections. A fifth subsection concentrates on the ratio of humans to robots as a cross-cutting issue of interest. The first four subsections describe the task, the workflow, and observed errors for each test task. They then discuss the results in terms of existing USAR practices and highlight any variances. If additional information was obtained during debriefing, it is included at the end of each subsection.

The human to robot ratio was 2:1 for the first three test tasks and 1.5:1 for the fourth test task. For the first three tasks using the Urban (Fig. 2a), the two humans involved were the IC and the robot operator. In the fourth task, the IC, two robot operators, and two Inuktun robots were involved (Fig. 2b). The IC was needed to direct the mission at hand while the operators concentrated on teleoperating the robots.

A. Task 1: Stair Climbing

The first task was for the Urban to navigate up the stairs (hot zone) to the fourth floor of the building while assessing the environment for structural integrity and environmental indicators (e.g., smoke). Task execution lasted 24 minutes during which the Urban covered 3.5 flights of stairs while stopping and scanning for signs of structural damage. The task ended when the Urban lacked sufficient power to climb further.

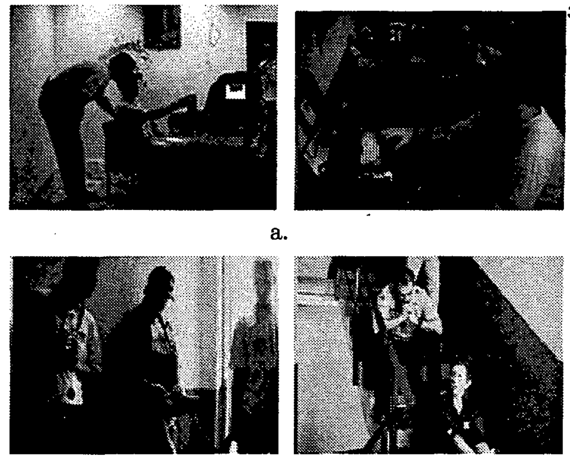


Fig. 2. Incident Commander and a) Urban operator executing the mission for the first and second test tasks and b) two Inuktun operators involved in the fourth test task.

The task yielded a basic script of actions and registered errors. The script was derived from the abstract directions given to the operator by the IC. The commands formed a basic ***stairwell search script*****: climb (5-10 steps), stop, rotate to look in the corners and up at the ceiling, repeat.**

During task execution, four errors occurred: one communication error, two collision errors, and one course correction error. The communication error was the most serious. In this instance, wireless Ethernet dropped out after the Urban had traversed 3.5 flights of stairs and the OCU was located on the first floor 20 feet from the stairwell. The operator had to relocate the OCU to the fourth floor entrance from the stairwell in order to re-establish communications (which is not feasible in practice). Two collisions occurred during the stair climbing of the first test task, and one course correction was made after the Urban slid backwards one step due to an operator miscue.

According to existing USAR practices, the task of assessing environmental and structural conditions while searching, or even transiting to a new location, is crucial to documenting hazards for subsequent crews and determining if the environment is compromised. Unsafe structures usually contain cracks in the walls, have fallen ceilings, uneven door frames, or uneven stairs, etc. However, Task 1 could have been partially achieved by a dog or performed in many conditions by a human. A search and rescue dog can climb stairs and determine if the entry floor is smoky; though, the dog will not enter a smoky area, unlike a robot. A human could have also performed the task. The human would have the advantage over the dog of being able to ascertain structural integrity of the stairwell. A robot would be useful for Task 1 only if the stairwell was already considered structurally unsound or otherwise not permissible for human entry.

The task execution also highlighted two conflicts that robots might have with existing USAR practices. First, if the field test were a true USAR incident, the Urban and OCU would have been taken to a safe point in, or near, the area of the structure that needed to be searched. This safe point could be up to 250 feet away, rather than within 20 feet. This increased distance would increase the chance for wireless communications to drop out. Second, according to Special Operations Chief Rogers, it took too long for the Urban to travel up the stairs. The operator could have physically carried the robot up the stairs, looked for cracks on the way up, and set the robot up in the stairwell on the fourth floor in much less than the 24 minutes taken to traverse 3.5 flights of stairs.

B. Task 2: Search

The second task was to teleoperate the Urban around the darkened and cluttered fourth floor of the building (hot zone) searching for a simulated downed fireman (a dummy dressed in complete fireman bunker gear) in a smoky building. The location of the fireman was only partially known to have been somewhere on the fourth floor. The task was analogous to searching for victims; however, a fireman wears clothing more visible in smoky conditions and is more likely to be in the open than a civilian. The robot entered the fourth floor from the stairway landing, found the fireman, and returned to the landing, for a total execution time of 18 minutes. The OCU was located in a room on the far end of the fourth floor, away from the landing and search area.

The existing practice in fire rescue is that rescuers are only allowed 10 minutes of search time in smoky conditions before retreating for air; rescue dogs are not capable of working in smoky environments. Radios and passive sirens are currently used to locate downed firemen. This may be similar to a victim shouting or banging on pipes or rubble. However, sound localization sometimes becomes difficult due to echoes. The searchers use either a right-wall-following algorithm or left-wall-following algorithm, recording their path in terms of openings (e.g., topological navigation using gateways). The topological navigation is easy to reverse for exit and easy to give directions to others. When they reach the fireman, they check for vital signs (movement of limbs or breathing, response to being touched or prodded, amount of air in air tank), then they return.

The robotic task began with the IC prioritizing the search area based on where the victim or fireman was last seen. The IC determined that the Urban would begin searching the South-side of the fourth floor as this was the last known location of the victim. The task execution yielded a ***topological search script*** of robot actions: **move forward, rotate and pan in order to detect signs of survivors in the current volume of space, simultaneously look for structural and environmental conditions, repeat while following the wall.** The IC consistently used topological commands such as "go right down the hallway" or "go in the first door on your right" to tell the operator where to drive the robot. Looking upward was particularly important since the firemen were concerned about hazards, such as signs of a "flash-over" or debris (ie. hanging wires). The Urban being used did not contain a camera that could tilt upward; instead the operator had the robot intermittently adopt the "angry crab" pose to elevate the front camera. It should be noted that the IC appeared to construct a mental topological map. The downed fireman was found based on the sight of a gloved hand, and the IC directed the robot to look for vital signs, including prodding the fireman with the robot and manuveuring to read the fireman's air gauge. The air gauge read empty (Fig. 3). The robot was then directed to return. No errors were observed.

Fig. 3. IC and operator used the Urban to inspect the air gauge.

During debriefing, three additional points were made by the fire rescue team members. When the robot finds a victim, it would be useful to deposit a strobe and audible alarm to guide rescuers to the victim. Another comment was that zoom would allow the operator to view details of the environment without further endangering the robot. This would have been useful when the Urban was inspecting the air gauge on the simulated fireman victim during the sec-

Sensor	Time Used Navigating	Time Used Searching and Examining	Total Time (s)
FLIR	0	372	372
CCD	173	95	268

TABLE II
BREAKDOWN OF THE TOTAL TIME THE FLIR AND CCD WERE USED INTO AMOUNT OF TIME USED TO NAVIGATE AND SEARCH/EXAMINE.

ond test task (See Fig. 3). The Urban had to literally climb on top of the victim to obtain a sufficiently close view for the IC. It did not appear that the presence of strobe lighting impacted task execution; the strobe effect was not noticeable due to the slow video update on the OCU.

In general, this task treated the robot as if it were a human with a greater air supply. However, robots in the future could possibly do better than a human if they could guarantee coverage of a void, carry structurally and environmentally specific sensors, generate and display topological maps to other fire fighters, and could generate and display metric maps.

C. *Task 3: Search with FLIR*

The third task was a repeat of Task 2 with two changes: a live victim in street clothes was used in place of the dummy and an Indigo Alpha FLIR was added to the Urban. However, only the IR camera or the CCD camera could be viewed at one a time on the OCU; therefore the IC had to determine the best view to be looking at throughout the course of the task. The robot entered the fourth floor from the stairway landing, found an unconscious victim, and returned to the landing, for a total execution time of 10 minutes and 40 seconds. Fig. 4 shows the Task 3 timeline starting at 11:07:20 and ending at 11:18:00. The horizontal lines show the time spent using either the CCD camera or the FLIR. The time above each line is the time spent using the sensor. For instance, the CCD camera was used first for 58 seconds before switching to the FLIR at 11:08:18. The two different line types represent the different jobs performed; the robot was either navigating through the environment or searching the environment for signs of victims or hazards and examining the victims.

The task execution proceeded as for Task 2 with two exceptions: the IC also had to determine which sensor to use to search with, video or FLIR, and how to best assess the condition of the live victim using the Urban and OCU. In this case, the IC alternated

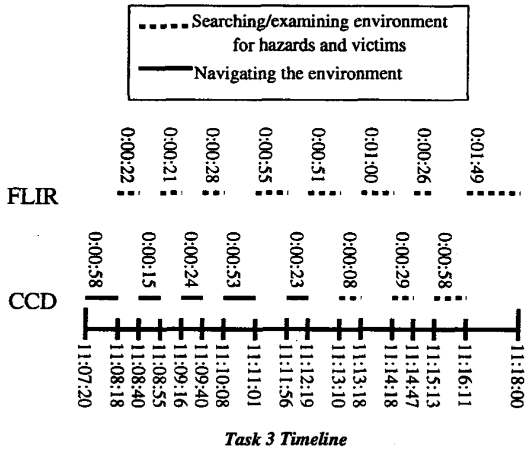


Fig. 4. Timeline for Task 3 showing when the FLIR and CCD cameras were used, how long they were used used, and what for.

between the FLIR and video throughout the search. The FLIR seemed to be the preferred modality for searching and examining the environment for hazards and victims, with video used as a backup; the CCD camera, however, was the preferred modality for navigating. Table II shows the FLIR was used for a total of 372 seconds versus the 268 spent using the CCD camera. The 372 seconds spent using the FLIR occurred during time spent searching the environment for victims or hazards. One the other hand, the time spent searching and examining with the CCD camera took only 95 seconds (less than a third of the total time the CCD camera was used). The remaining 173 seconds of CCD camera use was spent navigating through the environment. The 467 seconds of the total time taken to perform Task 3 was spent searching and examining rather than navigating, which took 173 seconds (27.0% of total time in Task 3 spent navigating).

Fig. 5 show the IR camera view and CCD camera view of the live victim. The live victim was more visible with the FLIR than the dummy. In order to detect signs of breathing, the IC asked for the robot to be still and to use the OCU cursor as a reference to detect slight motion. Motion in the chest area was detected and the victim was listed as being alive. The robot then returned to the starting area.

One communication error was observed. Communications dropped out when the operator was using the Urban to approach the live victim during the third test task. This resulted in loss of robot control and the Urban lurched into the victim.

In terms of existing USAR practices, the robot was used much in the same way a human rescuer outfitted with a FLIR would behave. During task execution

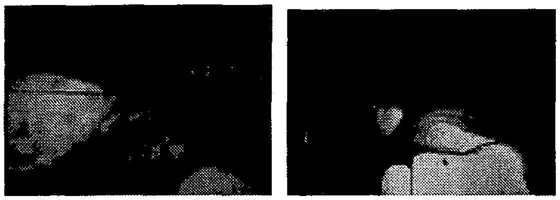


Fig. 5. View of live victim through the IR camera (left) and the CCD camera (right).

and debriefing both the IC and observers commented that it would have been helpful to have constant side-by-side or picture-in-picture video and FLIR camera views. A movable horizontal reference line would be more helpful than the cursor in detecting the breathing rate of a victim in camera view. It was also noted that the IC actually saw the IR signature of the live victim before the operator. The operator claimed, "I didn't see the arm due to concentrating on teleoperating the Urban." Also, the operator had not constructed any type of mental model or map.

D. Task 4: Entry through Hole

The fourth task was to teleoperate the two Inuktun robots, under the IC's lead, down a hallway, through an entry in a wall, into a room with a hole in floor (negative obstacle), enter the lower floor through the hole and survey it. The MicroVGTV (lead) robot was used to explore the environment. The MicroTracs System (secondary) robot was mostly used to spot the MicroVGTV.

Roof or ceiling entry of a void space is common practice in USAR. Typically a fireman makes a hole, explores the void below with a search cam (a camera on a two degrees of freedom stick), then enters the void, drills a new hole in the floor and continues. In this task, the tethered robot replaced the human and the search cam. The robot navigated to an existing hole, then fell into it hanging by the tether, and was lowered to the next floor or left suspended.

In terms of workflow, the mode of operation is *collaborative teleoperation* [2], where the robot operators depended on assistance from each other in order to traverse difficult terrain. In this case, the operators were sitting near each other and the robot operator of the lead robot would ask for advice from the operator of the secondary robot. A display with side by side views from both of the Inuktun cameras would have lessened the dependency between the operators, possibly decreasing the time taken to traverse an area.

No errors were observed during this task, but the purpose of using collaborative teleoperation was to eliminate or reduce errors. It should be noted that

Fig. 6. The MicroTracs System robot spotted the MicroVGTV while it traversed a pile of rubble during the fourth test task.

the MicroVGTV operator became disoriented and was unsure of the robot's orientation after it was lowered to the 3rd floor; collaborative teleoperation or better proprioceptive sensors would have been helpful.

Collaboration between the MicroVGTV operator and the MicroTracs System operator was needed to safely traverse the difficult terrain. During the fourth test task, the MicroTracs System operator spent approximately 5 minutes spotting the MicroVGTV when traversing a pile of rubble on the way to an entry hole to another room (see Fig. 6). The MicroVGTV robot OCU provided no means of informing the operator of its current pan angle or shape configuration. The operator was unaware of the robot's unstable shape configuration that would have caused the robot to tip over when navigating over rubble.

V. Conclusions

While the field test does not represent a statistically significant data set, it does contribute to a better understanding of USAR and human-robot interaction. Two prototypical sequences of searching were identified: *topological search* and *stairwell search.* These sequences could be encapsulated into fully or semi-autonomous behavioral scripts. The topological search script potentially has significant ramifications for developing a USAR research agenda; it indicates that topological navigation and mapping may be sufficient rather than the much more challenging metric methods.

Compared to existing USAR practices, the results suggest that robots working cooperatively with humans are superior to humans and dogs for searching and for exploring vertical voids. The utility of robots for climbing stairs was less clear; if robot platforms were improved, then the robots would be equal or superior. In terms of the activities within the task, with exception of tethered robots in Task 4, the robots served as surrogates for either dogs or humans. However, this is primarily a function of using a "fireman down" training ground, rather than a confined space test bed.

One metric for characterizing human-robot interaction is the human to robot ratio. In this study, the ratio was 2:1 for single robot tasks and 1.5:1 for collaborative teleoperation tasks. Each robot was controlled by a dedicated operator (a 1:1 ratio) while an IC oversaw the task and actually examined the video for relevant information. 2:1 may be reasonable for short term since it allows the immediate insertion of robotic technology into USAR. We note that this approach may be relevant for other robotic applications such as military operations in urban terrain where highly-trained specialists control the robots directly but the decision maker overseeing the activity does not have to be trained in robotics.

Another metric for characterizing human-robot interaction is the type and frequency of errors. The most common errors were collisions, which could be corrected by machine intelligence to reduce the impact communication time lags and cooperative robot teams to compensate for lack of sensors, followed by communication failures, which could be corrected with advances in wireless communication.

The findings also identified new issues in USAR: artificial intelligence support for ensuring complete search coverage, collaborative teleoperation, and topological mapping. Other important issues are improved platforms and sensors, mixed-initiative interfaces, and scripted navigation for areas like stairs which require complex motions and sensing. USF is continuing to pursue characterizing the USAR domain and developing AI for these areas.

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