Towards Combining UAV and Sensor Operator Roles in UAV-Enabled Visual Search

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ABSTRACT

Wilderness search and rescue (WiSAR) is a challenging problem because of the large areas and often rough terrain that must be searched. Using mini-UAVs to deliver aerial video to searchers has potential to support WiSAR efforts, but a number of technology and human factors problems must be overcome to make this practical. At the source of many of these problems is a desire to manage the UAV using as few people as possible, so that more people can be used in ground-based search efforts. This paper uses observations from two informal studies and one formal experiment to identify what human operators may be unaware of as a function of autonomy and information display. Results suggest that progress is being made on designing autonomy and information displays that may make it possible for a single human to simultaneously manage the UAV and its camera in WiSAR, but that adaptable displays that support systematic navigation are probably needed.

Categories and Subject Descriptors

H.5.2 [**Graphical user interfaces**]:

General Terms

Human Factors

Keywords

Ecological Interfaces, Human-Robot Interaction, Unmanned Aerial Vehicle, User Study

1. INTRODUCTION

Wilderness search and rescue (WiSAR) is a challenging problem because of the large areas and often rough terrain that must be searched. Because the search area grows rapidly and survivability drops considerably as time elapses, it is imperative that WiSAR searches be performed quickly [28]. Using a mini-Unmanned Aerial Vehicle (UAV) to provide aerial imagery of a search area has the potential for helping WiSAR, but a number of human-robot interaction problems must first be addressed. Because WiSAR efforts can cover vast areas, it is desirable to have as many well-trained people participating in the ground search as possible. This observation suggests that it is desirable to minimize the number of people required to manage the UAV so that more people can be used in other aspects of the search.

Unfortunately, experience in many aerial search applications indicates that multiple roles must be performed in order to use an UAV in search [14, 24]. The four primary roles are [13]: the incident commander, who is responsible for managing the search effort; the pilot or UAV operator, who is responsible for aviation and navigation; the payload or sensor operator, who is responsible for analyzing imagery and localizing potential signs of the missing person; and ground searchers. In this paper, we address the roles of the UAV operator and the sensor operator.

Importantly, the appropriate type of navigation depends strongly on whether the search is a hasty/heuristic search[1], an exhaustive search, or a search that evaluates high priority regions first. These three categories of search represent three of the four qualitatively different search types encountered in WiSAR [14, 28]. As we evaluate different display and autonomy paradigms, we will use the ability to recall a flightpath and the ability to quickly cover a region as measures of navigation quality. Similarly, we will use redundant observations, false alarms, and missed detection as measures of the quality of detection and localization. Throughout, we assume that aviation is performed by an autopilot.

Ideally, adding well-designed autonomy and information displays may make it possible for a single user to fill both the UAV operator and sensor operator roles. This paper evaluates what human operators may not be aware of as a function of emerging autonomy and information display designs. The paper uses observations from two informal studies and one formal experiment. Results suggest that autonomy and information displays may evolve to the point where it is possible for a single human to simultaneously manage a UAV and analyze video, but that adaptable displays that support systematic navigation are probably needed.

2. RELATED LITERATURE

The goal of this work is to support fielded missions in the spirit of Murphy's work [5, 7] by designing autonomy and

[1]A hasty/heuristic search reactively follows a trail of clues, such as footprints, rather than systematically covering an area.

HRI'08, March 12–15, 2008, Amsterdam, The Netherlands.

information displays that support WiSAR efforts. Related to this goal, there is a great deal of current research dealing with the human factors of (semi-autonomous) UAVs [17, 8]. Typically, a UAV engaged in a search task requires either two operators or a single operator to fill two roles: a pilot, who "flies" the UAV, and a sensor operator, who interprets the imagery and other sensors [31]. Lessons from ground robots suggest that it is sometimes useful to include a third person who (a) monitors the behavior of the pilot and sensor operators, (b) protects these operators, and (c) facilitates greater situation awareness [5, 7, 11]. We do not explicitly include this as one of the roles in WiSAR. Related to human roles, other work has analyzed how many unmanned platforms a single human can manage [26, 15, 9]. A common theme of this work work is that the span of human control is limited so that, for example, it would be difficult to monitor information-rich video streams from multiple UAVs at once, though it is possible to coordinate multiple UAVs a la air traffic control [22, 23].

In the WiSAR domain, literature related to aerial search is particularly relevant [20, 4]. Recent work includes not only an evaluation of the WiSAR problem domain [14, 13], but also the evaluation of heuristic algorithms for searching an environment characterized by a probabilistic description of the person's likely location [16]. Additional literature includes operator interface work for both UAVs and traditional aviation displays [6, 27, 1, 10, 32].

The exact type of interaction between a human and onboard autonomy varies widely across UAV platforms. At one extreme, the Predator UAV essentially re-creates a traditional cockpit inside a ground-based control station, complete with stick-and-rudder controls. At the other extreme are architectures employed by research UAVs that measure atmospheric composition by flying pre-programmed flight paths to obtain precise scientific data [12]. The interactions represented by these two extremes typify the extreme points of several adjustable autonomy scales [29, 19]. The presented work uses altitude, attitude, and direction control algorithms, plus the ability to autonomously travel to a series of waypoints. Thus, this work is between the extremes of teleoperation and supervisory control.

In addition to designing autonomy, it is necessary to create user interfaces that support efficient interaction. We use an approach for UAVs that is similar to the ecological interface design for ground robots developed by others [2, 25].

3. UAV OVERVIEW

The work presented in this paper is done using simulated UAVs. However, all of the control algorithms and user interface designs have been flown in one or more flight test with experimental UAVs[2] that are small and light, with most having wingspans of approximately 42"–50" and flying weights of approximately two pounds. The *airframes* are derived from flying wing designs and are propelled by standard electric motors powered by lithium batteries. Discussions with Utah County Search and Rescue indicated that at least 90 minutes of flight time was required for a reasonable search, so the BYU MAGICC lab created a custom airframe capable of staying aloft for up to 120 minutes while supporting an avionics sensor suite, a gimballed camera, and an autopilot.

[2]This description of the UAVs first appeared verbatim in [13]. It is included in this paper since to establish context.

The standard aircraft sensor suite includes 3-axis rate gyroscopes, 3-axis accelerometers, static and differential barometric pressure sensors, a GPS module, and a video camera on a gimballed mount. The UAV uses a 900 MHz radio transceiver for data communication and an analog 2.4 GHz transmitter for video downlink. The autopilot is built on a small micro-processor described in [3]. The UAVs are equipped with autopilot algorithms that stabilize the aircraft's roll angle, pitch angle, attitude, and/or altitude; the algorithms also provide the ability to fly to a waypoint. We will use the waypoint algorithm as the basis for the way the operator controls the UAV in the complete experiment.

4. INFORMATION DISPLAY PARADIGMS

One of the key factors that determines what a human operator can perceive is the way information is displayed. Although user interfaces for UAVs are currently evolving at a very rapid rate, there appear to be three complementary paradigms for presenting information. Although some information displays borrow ideas from different paradigms, this categorization is useful as we evaluate how autonomy and information display designs facilitate or inhibit search.

The first paradigm may be called *pilot-centered*. This para-digm seeks to replicate the kinds of sensors and gauges presented in a manned aircraft [21]. Extensions of a pilot-centered interface include recent ecological display development for better pilot support [30]. Because WiSAR personnel are not typically trained as pilots and because it is desirable to have training efforts focused on rescue and recovery rather than piloting, we will not address the pilot-centered paradigm in this paper.

The second paradigm may be called a *traditional display*. A traditional display uses multiple windows to present a map, live video, and perhaps annotation and communication. For example, Figure 1 presents the flight map window (on the right) that shows a map with the full flight path and current location of the UAV marked. As the craft flies over terrain, the live video window (center) shows video received by the UAV camera. The marking window (left) provides a map of the same location as the flight map window and allows UAV operators to annotate the map with relevant items of information.

Anecdotal evidence in field tests suggests that it is difficult to integrate map information with video information in a traditional display. In an informal study, we simulated a situation where the sensor operator is isolated from the UAV operator by requiring human participants to identify targets from video obtained during a pre-programmed flight. The conclusion from this informal study is that it is difficult for an isolated sensor operator using a traditional information display to distinguish between redundant targets.

Five unbiased participants observed four, five-minute flights on a 19-inch LCD monitor. The four different flight paths covered approximately the same distance, but followed differently shaped paths over a wide range of terrains. Participants marked targets using a regular optical mouse and were paid $10 for their participation.

During the four flights, four different video presentations were shown to participants in random, counter-balanced order: downward, downward-persistent, angled, angled-persistent. The downward trials simulated a camera pointing directly out of the bottom of the craft; the angled trials simulated a camera mounted such that the center of the camera

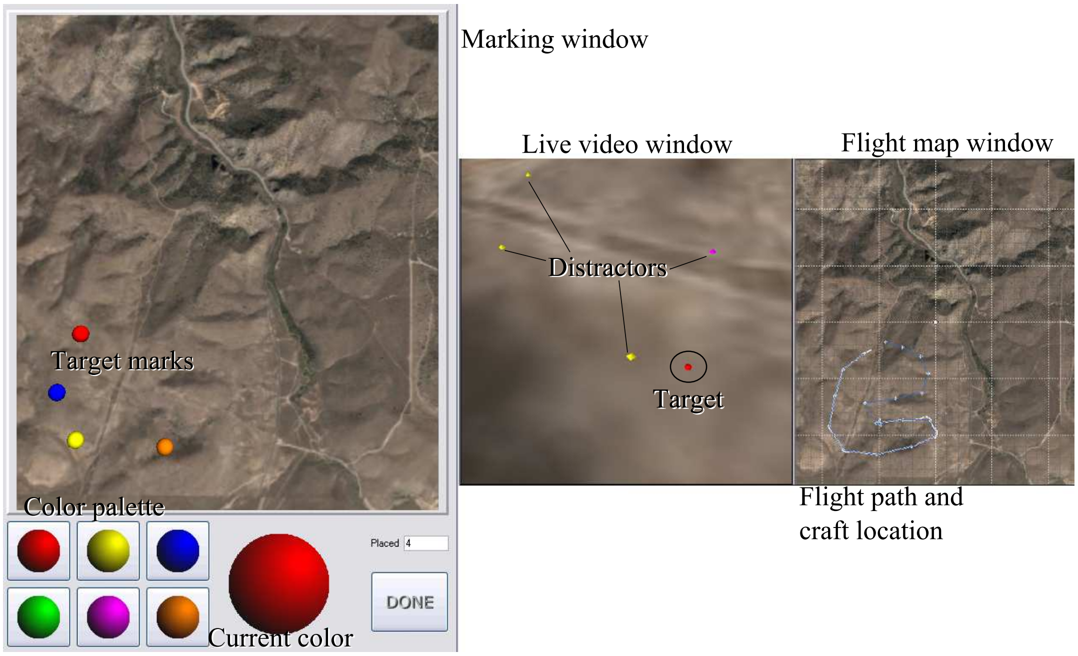


Figure 1: Traditional multiple window display.

pointed 45 degrees from the bottom of the craft. The camera had a 30 degree field of view. The persistent trials assumed a gimballed camera that was aimed so that the camera maintained a constant angle (straight down or 45 degrees from straight down) with respect to the normal from the UAV to the ground. The non-persistent trials kept the camera fixed with respect to the craft so that when the UAV turned one direction, the video footprint extended in the other direction.

The lesson from this informal study is that, although detection was easy, correctly localizing the target was very hard to do given the display. This is indicated by the high number of targets that were redundantly marked because participants could not tell that they had seen and localized these targets before. Although there were only 10 targets visible in each experiment trial, participants marked, on average, 16.35 targets per flight. Additionally, three of the five participants commented on the difficulty in discerning redundant targets. From video tape of participant faces, we qualitatively observed that participants split their attention fairly uniformly across the three different windows, spending one to five seconds on each window. This suggests that a key contributing factor to redundant target identification was that the participants' attention was stretched across the three different windows.

The third paradigm may be called an *integrated display*. By contrast to the traditional display, integrated displays may include satellite imagery, contour plots, a representation of the UAV, the camera footprint, and annotation information projected onto a simulated terrain. For example, Figure 2 displays an iconic representation of the UAV in a synthetic terrain map, with a tethered video heuristically projected to the surface of the terrain. Note that the "carrot" label in the figure will be discussed in the next section.

Evidence from ground robots indicates that an integrated display paradigm may make searching for objects easier than

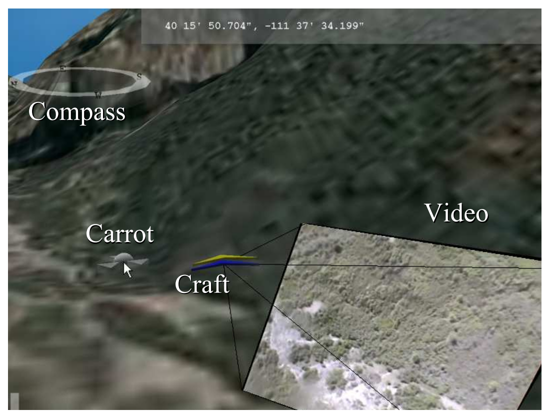


Figure 2: An integrated display.

with traditional displays [25]. In an informal experiment, participants analyzed video from a preprogrammed flight over simulated terrain. The conclusion from this study is that an isolated sensor operator using an integrated display is largely unaware of the path flown by the UAV.

Eight participants were instructed to localize targets and to remember the flight path. The ability to remember the flight path hypothetically provides information about whether a human operator could localize targets while efficiently performing a systematic search. Since remembering what has been searched is necessary for efficiently covering a search area, having some recollection of the flight path would be necessary if a single human were to perform both the UAV operator and sensor operator roles simultaneously. Throughout each flight, targets (spheres) and distractors (pyramids) were visible in the simulated video. At the end of the flight, the interface perspective smoothly zoomed out to show the entire map and instructed the participants to do their best to draw the path the UAV flew. Each flight covered the same distance, had no overlap, and consisted of five straight segments with four turns of either forty-five degrees or ninety degrees. Participants observed video from two nominal displays (a chase perspective and a north-up map perspective) and from three combination displays that switched perspectives during the middle of the experiment.

Results indicate that targets were easily detected in this experiment, but participants were generally incapable of remembering the automatically executed flight path while focusing on the detection task. Paths seemed almost completely random and participants admitted that they had no clue what the actual flight path was. We tried allowing subjects to use a paper and pencil to help with remembering the flight path. With a paper for taking notes, participants performed better at remembering the shape of the flight path, but had very little sense of scale or location or even the relative lengths of the five flight segments. This indicates that they did not know where the craft had actually flown, but just that it had made certain turns. We attempted to give a sense of scale and location by showing on the map where the craft started and stopped but participants still failed to draw the flight path with any degree of recognizable accuracy.

5. AN INTEGRATED DISPLAY AND ACTIVE SEARCH

The two informal studies suggest that requiring an operator to integrate information from multiple sources makes it difficult to unambiguously identify targets, and that requiring an isolated sensor operator to recall the path is very difficult. In response to these observations, we hypothesize (a) that an integrated display supports localization better than a traditional display, and (b) that giving operators navigation control provides them greater awareness of the path. In this section, we present an experiment that tests these hypotheses. The experiments include the following elements: full autonomy for aviation, a very simple detection task, and autonomy that supports human-directed navigation.

More precisely, we explore the effect of different information displays on a reactive search task using the display shown in Figure 2. We studied how well an operator with minimal training could perform a search task operating the interface using four common control perspectives: chase, north-up, track-up, and split/full-map display. In the chase perspective, the operator views an integrated map and UAV icon from a virtual position behind and above the UAV. In the north-up perspective, the operator views an integrated map and UAV icon from directly above the UAV, with the orientation of the map always north-up. In the track-up perspective, the operator again views an integrated map and UAV icon from directly above the UAV, but the orientation of the map changes so that the heading of the UAV is always to the top of the screen. The split display is similar to the north-up display, but from a much more distant perspective, which means that the operator must rely on a secondary video display since the integrated video has too little detail to detect targets.

5.1 Design

Participants used each of the different perspectives to find targets randomly distributed according to each of three different distributions: uniform, gaussian, or rectangular path. The uniform and gaussian distributions are restricted to a sub-area on the map that covers approximately one-fourth of the map's area. The path distribution is shown in Figure 3; in the figure, the light speckles indicate targets and distractors, and the shading represents the probability density function from which the targets and distractors are sampled. Importantly, the three different distributions correspond closely to the three previously mentioned WiSAR search tactics: hasty, high-priority, and exhaustive search. Having targets distributed uniformly across a sub-region of the terrain suggests an exhaustive search of that area. Having targets scattered according to a Gaussian distribution suggests a high-probability-prioritized search pattern. Having targets distributed closely along a constrained path suggests a hasty search.

Figure 3: Rectangular path distribution.

Colored spheres and pyramids were placed in the world to represent targets and distractors, respectively. Both types of objects followed the same distribution, but there were 300 pyramids and 10 spheres. Subjects were instructed to locate and mark the spheres. The pyramids served as distractors (to keep the participant from simply marking any object that stood out from the earth-toned terrain imagery). Pyramids also indicated the probability distribution so that if there were a large number of pyramids in an area, it was more likely that there was a sphere in the same area. The pyramids fill the role of minor environmental clues such as game trails or vegetation that may not appear in satellite imagery, but give some hint about where a more important clue may or may not be when seen through the live video.

Localizing the spheres was accomplished by using the mouse to left-click on the terrain location where the subject believed the sphere to be. When participants marked a location, a spherical marker stayed in that location. Performing a left-click on an existing mark allowed the subject to drag the mark around, while performing a right-click deleted the mark. Participants also had the option to press the space bar to take a snapshot of the video. The snapshot left a still frame of the video at the location the camera was pointing to when the snapshot was taken. Taking snapshots was not necessary for the task, but was a tool participants could use to get a better look at the video of a particular location or to help mark where the craft had been.

Participants operated the UAV with the mouse using a "stick and carrot metaphor" [34]. The "carrot" was a distinct marker (Figure 2) rendered onto the synthetic terrain that would follow the mouse cursor as long as the Control key was down. When the test subject released the Control key, the marker stayed where it was and the craft continued to fly toward the mark using the autopilot capability to autonomously fly to the waypoint. When the UAV arrived at the mark, it first crossed over the point and then began to orbit the mark until it was moved. Typically the onboard camera pointed thirty degrees forward from straight down (with respect to the craft), but when the UAV began orbiting a point, the gimballed camera was aimed so that the center of the camera focused on that point. This same control method was used for all four perspectives. The operator control interface connected to Aviones, an open source, moderate-fidelity, physics-based simulation that runs the same autopilot code and flight-dynamics model as the physical craft. The simulator generates imagery as it would be seen by the UAV camera using a synthetic terrain model. The experiment used a 19-inch LCD monitor for the primary display and a five-inch auxiliary LCD monitor that showed the raw video.

Twenty-one naive human subjects participated in the experiment. Participants received $12 for their time. Test participants were given a sheet of directions and trained on each interface. For each perspective, training included having subjects practice controlling the craft, taking snapshots, and marking (localizing) targets. Subjects participated in twelve experimental trials and four practice trials for a total of sixteen trials. Each of the sixteen trials took place in similar synthetic environments, each with a large flat central area and small hills off to the sides. Each participant controlled the craft through all four experimental perspectives, which were presented in randomized and counterbalanced order. After each experimental trial, participants answered three questions about the relative difficulty of the task and then went on to the next trial. The study ended with a few more general questions about the interface.

5.2 Results

The first observation is that performance shows a strong learning effect across all experiment conditions. Figure 4 shows that true positive marks generally increase while the subject uses a particular control mode and fall slightly when the participant switches to a new perspective. Similarly, false positive and redundant marks[3] fall fairly consistently over time, rising slightly with the perspective changes.

The second observation is that the split/full-map perspective is significantly worse ($p<0.05$) in all measures except redundant marks; see Figure 5. Additionally, participants ranked the split display as more difficult than all other perspectives ($p<0.0005$). Although the video footprint is visible in the split/full-map perspective, the low video resolution forces participants to rely on the raw video monitor to detect targets. Many participants commented that they used the raw video monitor only for the full-map perspective and that they disliked it.

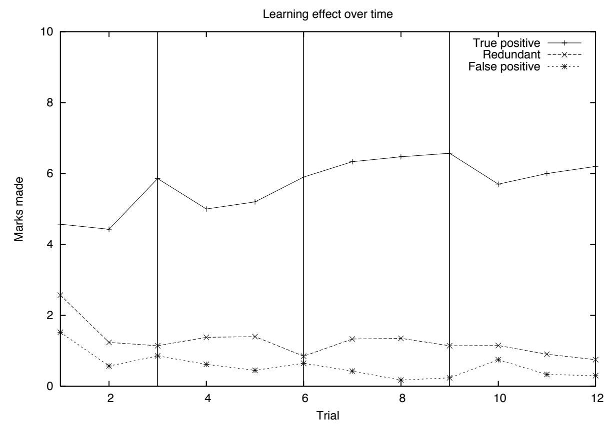


Figure 4: Learning Effect. The vertical lines indicate a change in the perspective used in the experiment.

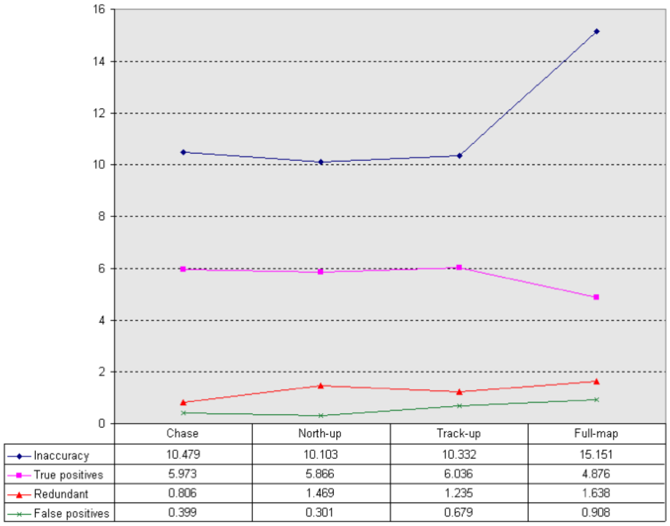
In the split/full-map display, participants directed the craft using the interface screen while trying to simultaneously monitor the raw video screen for targets. Upon detecting a target, they returned their attention to the interface screen and searched for the video footprint in order to localize the object on the terrain. Accurate localization required mental rotations to correlate the video with the terrain. To cope with this difficulty, several participants used the snapshot feature for the full-map perspective trials. Participants could concentrate on the raw video monitor with one hand on the mouse and the other on the keyboard. When a participant detected a target from the raw video, participants took a snapshot. They then switched their attention briefly to the primary monitor, localized the snapshot, and placed the sphere mark. Participants who used this strategy qualitatively did better with the full-map perspective than those who did not, but still worse than with other perspectives.

The third observation is that the three distributions vary significantly in difficulty. Performance is generally best for the path distribution and worst for the uniform distribution (see Figure 6). The uniform distribution demonstrates more redundant marks than the path distribution ($p=0.0435$) and fewer true positives ($p=0.0263$).

One reason that the path distribution may be easier is that the path distribution suggests an obvious coverage strategy: find and then follow the path. Following the path quickly covers the full probability distribution. Searching the Gaussian distribution from the center outward quickly accumulates probability at the beginning and gradually tapers off with time. Finally, a uniform probability distribution over a rectangular area can be accumulated at a constant but somewhat slow rate.

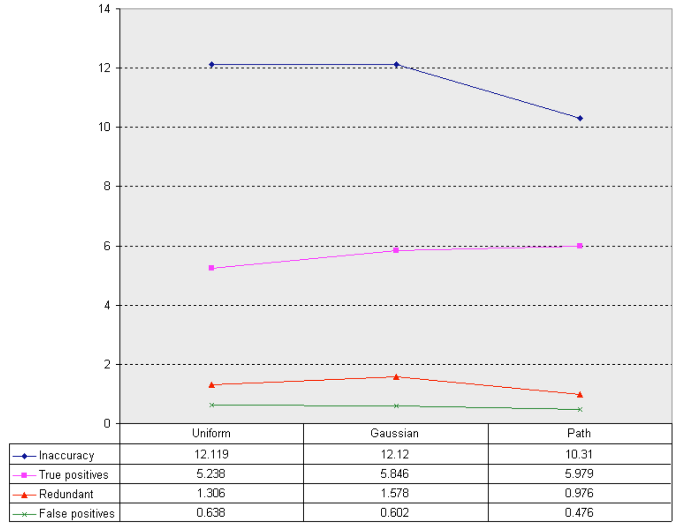
The fourth observation is that the track-up, north-up, and chase perspectives show roughly comparable levels of performance; see Figures 7 through 9, which group various performance metrics first by perspective and then by distribution. Although the chase perspective produced more

[3]A redundant mark occurs when a subject places two or more different marks for a single target. Redundant marks indicate that the subject was not able to determine that they had previously seen that target; redundant marks indicate a limitation of situation awareness. Note that the only differentiating feature between targets in our experiment is their color, but targets in a real search may be uniquely identifiable. Thus, redundant marks may be less of a problem in a real search than in this experiment.



	Chase	North-up	Track-up	Full-map
Inaccuracy	10.479	10.103	10.332	15.151
True positives	5.973	5.866	6.036	4.876
Redundant	0.806	1.469	1.235	1.638
False positives	0.399	0.301	0.679	0.908

Figure 5: Performance means according to perspective.



	Uniform	Gaussian	Path
Inaccuracy	12.119	12.12	10.31
True positives	5.238	5.846	5.979
Redundant	1.306	1.578	0.976
False positives	0.638	0.602	0.476

Figure 6: Performance means according to distribution.

true positives than track-up (p=0.0633), subjects generally performed comparably well using the chase, north-up, and track-up perspective. This is notable because other studies have found improved performance and operator preference using a track-up perspective [33, 18]. This may be because the other studies used an aviation-based control method where commands are given with respect to the craft (e.g., turn right or left). A track-up perspective helps the operator avoid confusing his or her own left with the craft's left. The carrot and stick control metaphor, on the other hand, is navigation-based.

The fifth observation is that there are several two-way interactions between perspective and distribution. Specifically, chase perspective and north-up perspective are significantly better than track-up and split/full-map perspectives for redundant marks under a uniform distribution. Additionally, the chase perspective is significantly better than the other three perspectives for redundant marks under the gaussian distribution and the path distribution. By contrast, the north-up perspective is significantly better than the other three perspectives for false positives for the gaussian distribution, though the chase perspective is better than the other three perspectives under the same metric for the path distribution. This observation is important because it suggests that the best perspective for detecting and localizing a target depends on the type of search being performed. We summarize this conclusion and others in the next section.

6. CONCLUSIONS AND FUTURE WORK

Although it does not yet merit a strong conclusion, the observations reported herein allow us to speculate that it may be possible for a single human to simultaneously navigate an area while localizing objects. Achieving this speculated objective requires that trustworthy aviation is available, that detection is sufficiently easy, and that some form of support is available for systematic and efficient navigation.

In support of this speculation, the observations from the informal studies and the formal experiment suggest a number of less speculative conclusions. The first conclusion is

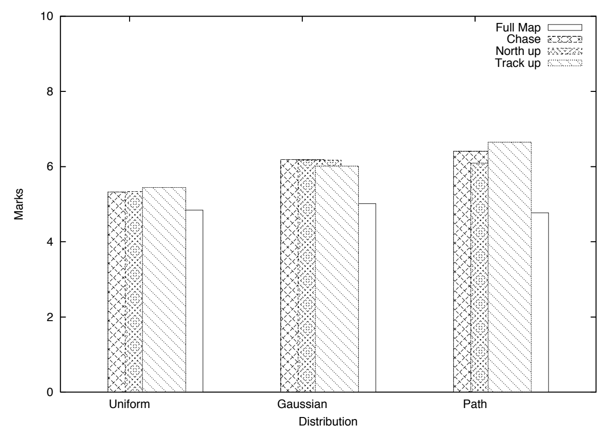


Figure 7: True positive marks

that having the UAV, camera footprint, and annotation integrated into the map appears to improve the ability to localize targets. This should not be surprising since it should be easier to detect a redundant sign if that sign is displayed next to video information in a display; by contrast, traditional displays require an operator to mentally integrate video, map, and annotations. The conclusion that localization is easier in an integrated display is strengthened by the observation that, under the split/full-map display conditions, participants who took a snapshot when they detected a target and then used this snapshot to localize the target performed better than those who did not; having the snapshot integrated into the map reduced the difficulty of integrating information from multiple windows.

The second conclusion is that efficient navigation is more challenging for some search types than others. This conclusion is supported by the observations that the path distribution generally produces better performance than the other

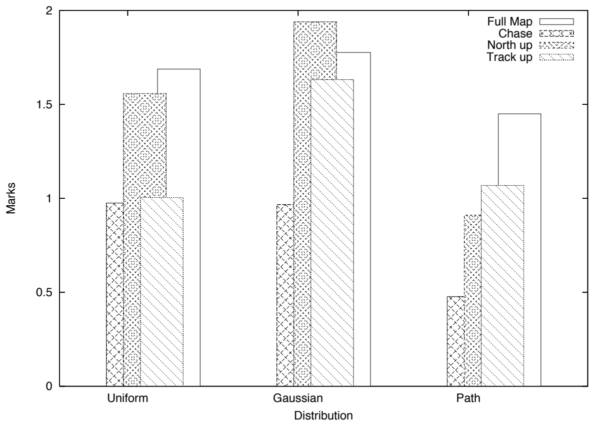


Figure 8: Redundant marks

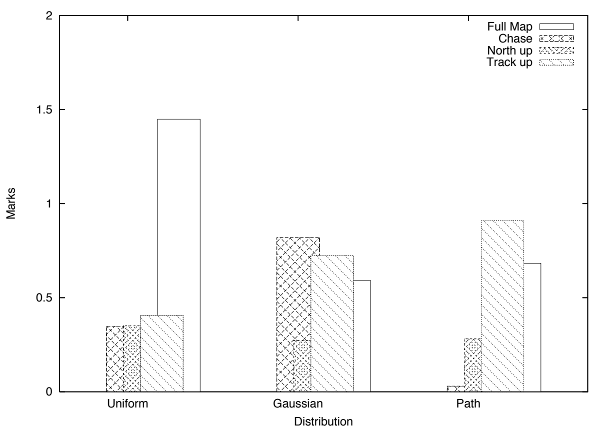


Figure 9: False positive marks

distributions. Simply put, following a path of clues is easier than systematically searching an area beginning in high priority areas and ending in low priority areas. As it relates to the speculation that it may be possible to combine UAV operator and sensor operator roles, the performance difference between search types suggests a caution and a direction of research. This caution is reinforced by the observation from the second informal trial that a passive sensor operator may be generally unaware of the path followed by the UAV operator. However, if "coverage maps", such as the preliminary one reported in [14], are used to help an operator understand the quality of the search path, it may still be possible for an operator to perform an efficient high-priority or exhaustive search while simultaneously localizing targets. Indeed, a coverage map could be projected into a path plan so that the operator could follow an efficient path without becoming a passive sensor operator.

The third conclusion is that exhaustive and high-priority searches are probably done more effectively from a north-up perspective than from a chase perspective; conversely, a hasty search is probably done more effectively from a chase perspective. Simply put, the observations suggest that hasty searches require more craft-based path changes, while complete searches require more map-based planning. This observation suggests that research is needed into how display perspectives should be changed depending on the type of search that is being performed. Since an incident commander may want to change from an exhaustive search to a hasty search if new evidence surfaces [28], the need for adaptable displays may be key for fielded searches.

In addition to future research into adaptable displays and coverage maps, we have largely ignored aviation and detection. Although the UAV autopilot supports a wide range of aviation, work is still needed to perform good height above ground (HAG) maintenance. It should be noted that in at least three field trials, the absence of good HAG support caused problems in the search. A second area of research is the continued improvement of image enhancement and mosaicking techniques for improving detection. Initial work in the importance of temporally local image mosaics indicates that such mosaics make detection much easier [14], but several detection-relevant problems persist including low resolution and poor color.

Acknowledgements

The authors the reviewers for their helpful comments. This work was partially supported by the National Science Foundation (grant 0534736), by the Utah Small Unmanned Air Vehicle Center of Excellence, and by a Mentored Environment Grant from Brigham Young University. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of these supporting organizations.

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