User Experience Design for Human-Machine Teaming in Commanding a Distributed Constellation of Unmanned Assets in Search and Rescue

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Abstract – Search and rescue missions are time-sensitive, with their duration impacting survivability. Unmanned aerial vehicles (UAVs) are increasingly shortening response time, accelerating area coverage, and informing resource allocation. However, interactions of UAVs and human operators pose challenges, for example, related to understandability and trust in automation. This work seeks to facilitate human-machine teaming in designing an on-the-loop user experience with a constellation of UAVs as they narrow search areas by locating and triangulating mobile phone signals using dynamic co-fields autonomy. First, an abstraction-decomposition hierarchy is built to represent underlying values and requirements of the domain. Second, user interfaces are designed to reduce UAV and phone positional uncertainty over time, monitor power, communications, and other information per asset, and empower the operator to influence drone behavior. Their design includes spatiotemporal representations of search areas, UAV positions, communications signals, as well as notifications. Finally, user evaluation was conducted with domain and usability experts.

Index Terms – user experience, human-robot teaming, human-automation interaction, graphical user interfaces.

INTRODUCTION

Search and Rescue (SAR) missions are time-sensitive. The survivability of missing persons decreases as mission duration increases. Therefore, the use of unmanned aerial vehicles (UAVs) in SAR missions can improve mission response by shortening response time, accelerating area coverage, and providing information that enables a more efficient allocation of resources. Aerial vehicles help reduce the risks posed to ground personnel by performing initial sweeps of dangerous areas, and allowing personnel to more rapidly and efficiently focus their time and efforts.

Although cell phone service is unavailable in many remote recreational areas, most hikers still routinely carry their mobile phones. For this reason, one method of aiding SAR is through the triangulation of mobile phone signals using positional information acquired from UAVs. However, interactions between semi-autonomous UAVs and human operators pose challenges related to understandability and trust in automation. Schaefer, et al. (2017) explain that one way to help address these challenges is to communicate the automation's intent and create shared mental models within these human-machine teams, thereby engendering trust.

Prior research in automation has considered trust at multiple levels of abstraction, leading to several key considerations. First, the unambiguous delineation of roles and functions is crucial. Cummings, et al. (2019) detail how operators must understand the limits of the automation's functionality to avoid losing situational awareness and suffering from automation bias. Second, understandability and trust are required between human operators and automated systems and are fostered by providing information to the operator on the intentions and reasoning processes of the automated systems. This provision helps provide transparency to the operator and helps to avoid the negative effects associated with misinterpretation of the automation's intent (Schaefer et al., 2017). Third, semi-autonomous control is more effective than pure teleoperation in addressing human situational awareness (Hong et al., 2019). Moreover, there is a distinction between human-in-the-loop and human-on-the-loop systems, where operators might interact with a fleet of multiple autonomous vehicles or agents altogether as one unit.

With supervisory control interfaces, Zhang et al. (2016) note a need to focus on supporting the operator as an information analyst and a decision-maker. To this point, different levels of information abstraction must be provided to the operator in order to diagnose issues and gain situational awareness between machine capabilities and mission progress. Well-designed interfaces reduce the cognitive workload of an operator, which allows her or him to expend more energy on the task at hand (Zhang et al., 2016).

The work herein develops a user experience to facilitate human-machine teaming between human operators and a constellation of UAVs to expedite and lower inherent risks in search and rescue missions. The design of the user interfaces seeks to afford the operator to oversee constellations of three or more UAVs, as opposed to direct control, as with single UAVs. Operators are able to command and monitor incoming data of the whole fleet altogether as one unit.

METHODS

I. Process for Commanding Distributed Constellation of UAVs

Being able to use UAVs to quickly localize a lost individual's cell phone signal may greatly improve the efficacy of search and rescue. When a SAR team is notified of a missing individual, a mission is created. During a mission, the human operator's tasks include deploying either part of or an entire constellation of drones, overseeing flight operations and cell phone signal triangulation, and calling the constellation back when a mission is complete.

The unmanned assets use dynamic co-fields autonomy, where UAVs choose their heading based on a weighted average of several vectors representing influential factors. These influence vectors create attraction of the UAV towards phone signal locations, communications links, unexplored areas, and the home base.

II. Requirements of Search and Rescue Environments

The abstraction-decomposition hierarchy shown in Figure 1 was built in close collaboration with multiple stakeholders to distill the values and requirements of the mission environment. The matrix distributes functions across levels of abstraction and across degrees of decomposition (Lintern, 2016). These functions are explicitly addressed at each level of abstraction for the subsequent mapping of information onto the user interface. As well, information and functional requirements are derived from this hierarchy, and are directly addressed in the interface design.

IIa. Information Requirements

Mission progress over time: Information about an ongoing mission, including the size of the search area, location and heading of UAVs, coverage of the search area, and uncertainty around detected phone signals are necessary.

Unmanned asset operational status: Operators must be alerted of potential non-nominal states or changes in UAV function. Key elements of UAV functioning are location, communications links, and battery life.

Distributed constellation status: Operators must be able to understand why UAVs make navigational decisions. Such decisions are influenced both by mission elements, such as phone signal and home base locations, and constellation elements, such as communications links and unexplored areas.

Phone signal localization: Operators must be able to view all detected phone signals and their respective location uncertainties. This affords the triangulation of phone signals over time and decision making on those which might not belong to the lost individual.

Operational conditions: Weather and terrain can greatly impact mission success. Operators must evaluate key terrain features and inclement weather that affect UAV function.

IIb. Functional Requirements

Spatial-temporal visual element display: A spatial representation of the SAR environment enables operators to understand the context in which a mission is taking place. A temporal element allows operators to track changes over time in the mission and asset constellation.

Mission Management: As part of mission management, an operator must be able to create, direct, monitor, and archive missions. Since it is possible for multiple missions to run concurrently or for a mission to pause and restart, a

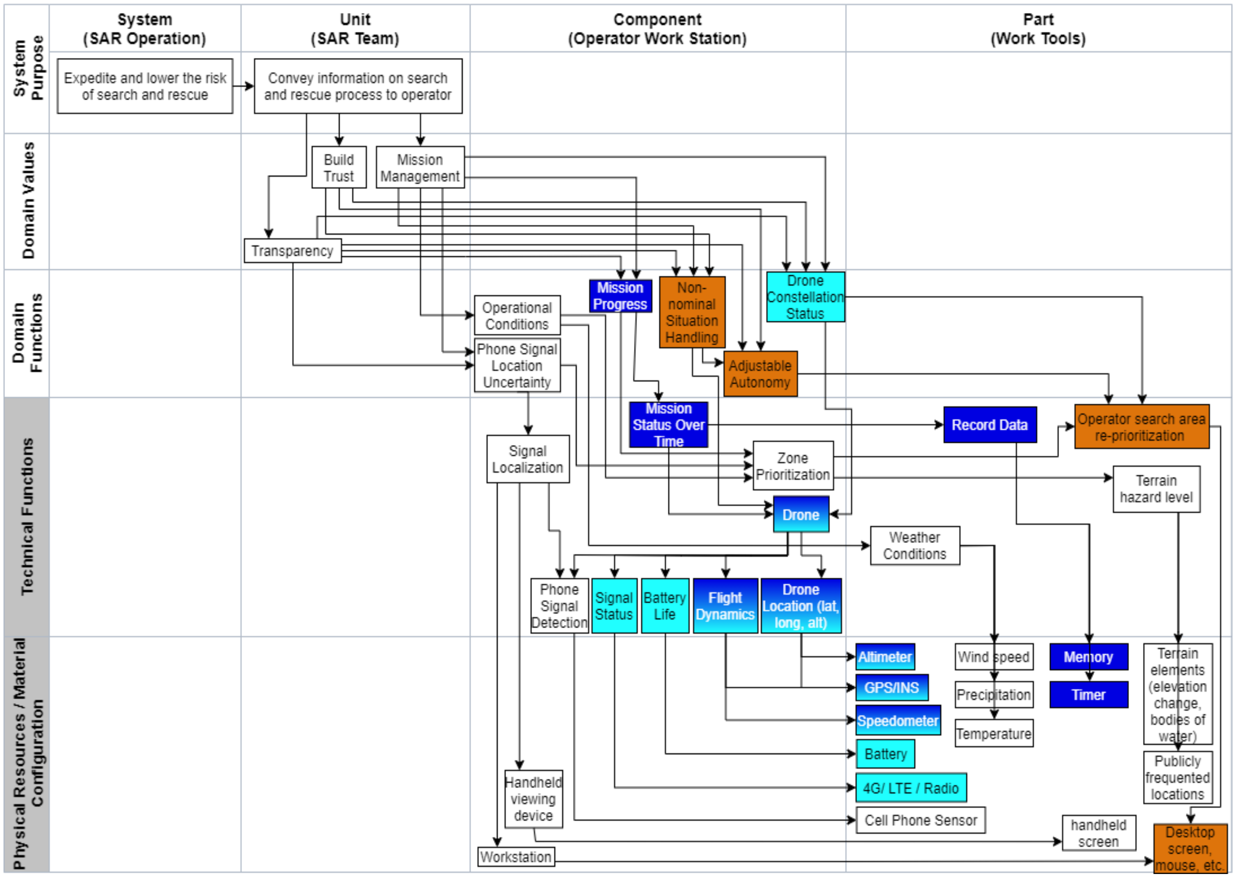


Figure 1. Abstraction-decomposition hierarchy of a distributed constellation of unmanned assets for search and rescue. Boxes colored in blue corresponds to positional uncertainty, cyan to asset monitoring and orange to asset control.

management system that groups specific mission information and mission tasks is essential.

Unmanned Asset Control Capability: This control capability allows the operator to influence specific UAVs within the constellation by changing its behavior. This capability provides a way for an operator to direct the UAV without taking full control.

Problem Diagnostic Capabilities: In cases of non-nominal UAV activity, the operator must be notified immediately and informed of which system elements are affected. The alert system triages information into a prioritized log. Redundant information will also be provided to inform the operator of constellation inconsistencies.

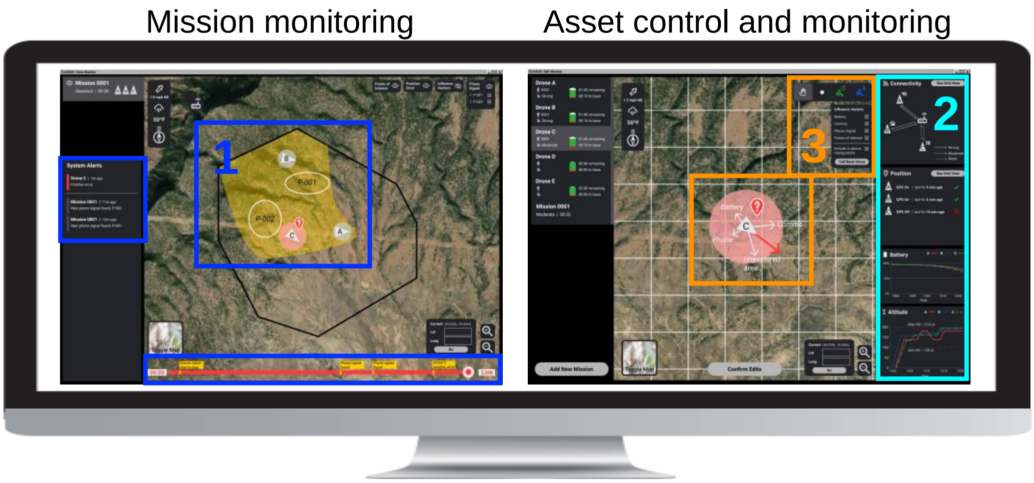
III. System Design & Implementation

Graphical user interfaces were developed to achieve three main goals, 1) reducing UAV and phone positional uncertainty over time, 2) monitor assets, and 3) control assets. In Figure 1, these goals are achieved through functions and resources highlighted where blue corresponds to positional uncertainty, cyan to asset monitoring and orange to asset control. The user interfaces seek to enhance decision making and overall performance of the human-machine team, build trust between the operator and UAVs, and enhance transparency to keep the operator updated. In particular, the interface designs include spatial representations of search areas, drones, communications and phone signals, as well as real-time and persistent notifications of mission-related events. The two monitors in Figure 2 provide a high-level overview.

Reducing UAV and Phone Positional Uncertainty: Positional uncertainty of the drones over time is represented in the left-hand interface shown in Figures 2 and 3. Figure 3A displays the drones covering search area corresponding to their location and the associated phone signals in the area. Search area mapping and phone signal triangulation depend upon the position error or uncertainty surrounding a drone's location. Figure 3A then shows the uncertainty bubble surrounding the drone to inform the operator of the uncertainty associated with the drone's position. Phone signal detection and progress over time is shown in Figure 3B, where the operator may view changes over time with respect to a drone's progress. If a drone's positional uncertainty crosses a specific threshold that the operator should be alerted to, the operator will receive an alert as shown in Figure 3C in the system alerts widget. All of these factors correspond to the blue elements in the work domain analysis shown in Figure 1. The altimeter, speedometer, GPS and INS systems all relay positional uncertainty information to the operator over time in order to keep track of mission progress.

Monitoring Assets: The interface also provides comprehensive monitoring of various attributes. Figures 4A and 4B display the status of individual UAV communication lines and their position. Figures 3C and 3D also display battery and altitude information, which show battery life associated with each drone and altitude of each drone over time. These elements allow operators to quickly identify sharp changes in battery life or altitude, which may indicate non-nominal behavior. In order to properly monitor assets, multiple levels of abstraction provide the operator with a deeper understanding of drone behavior. In Figures 3A and 3B, the operator is shown two levels of information, the left widgets acting as higher-level overviews of systems and the right widgets providing lower-level direct connections and measurements. The levels map directly onto the work domain analysis in Figure 1 as the cyan elements, with each of the drone's technical system components on the lowest level reporting measurements and each drone reporting the status of its system to the operator. These levels of abstraction provide the operator with diagnostic capabilities.

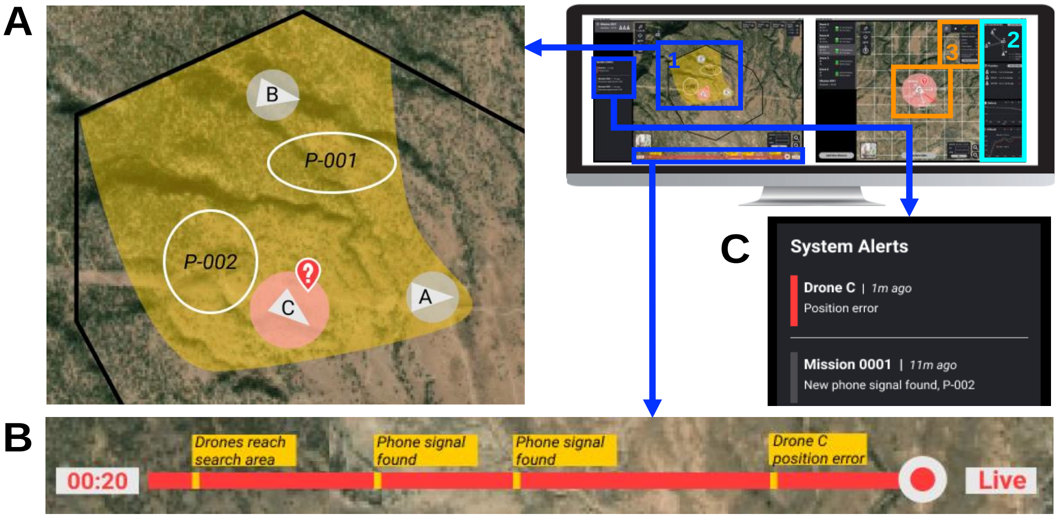
Controlling Assets: The third goal of the system is to establish control over the constellation of semi-autonomous assets. In Figure 3E, the operator can exert influence on the drone's behavior by selecting influence vectors in calculating its direction. The operator can also set points of interest for


Mission monitoring

Asset control and monitoring

Figure 2. Dual-monitor user interface layout. The left side is the main screen, and provides a high-level view of mission progress. The right screen has a troubleshooting and editing capabilities, and provides in-depth information and allows the operator to make changes with regards to both mission information and for individual and collective UAV rerouting. Boxes labeled (1) Blue, (2) cyan, and (3) orange indicate key interface elements related to positional uncertainty, asset monitoring, and control, respectively, which map to the abstraction-decomposition hierarchy in Figure 1.

each asset in the event new information arises that the operator wants to share with the constellation. A shared mental model is created in the human-machine team as the operator understands the influences the drones are working under and the operator can share new information with the assets. With this, operators can develop trust in the system with greater understanding of the underlying automation. Elements of asset control are marked in orange in Figure 1. They deal with the handling of non-nominal situations where the operator is required to react and inform the system of new information.

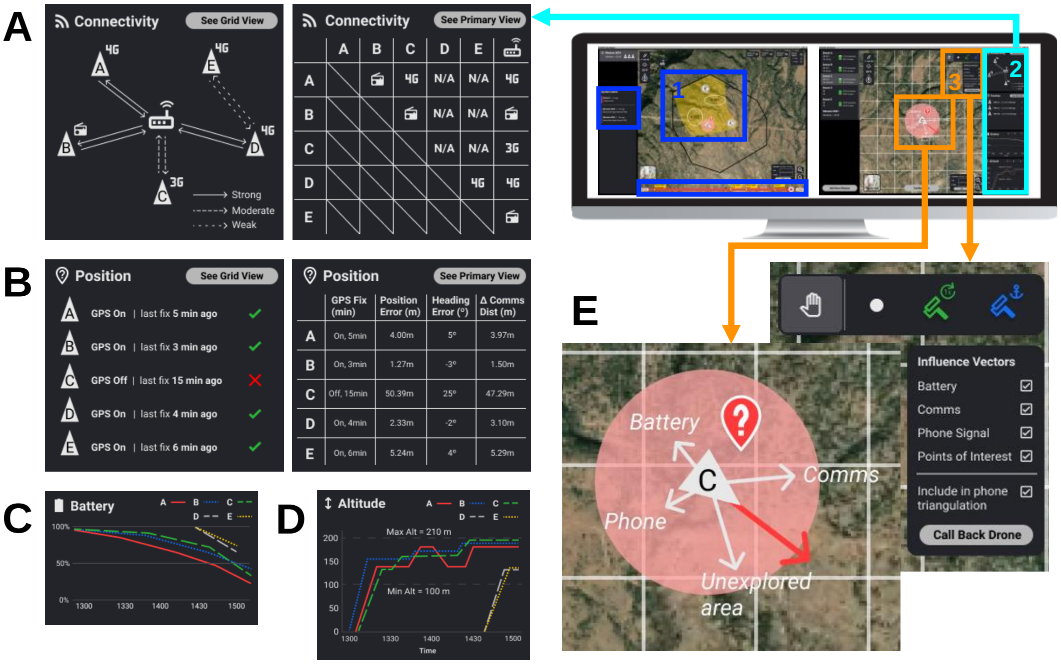


System Alerts

Drone C | *1m ago*
Position error

Mission 0001 | *11m ago*
New phone signal found, P-002

Figure 3. Insets of interface elements from left screen of Figure 2. (A) Mission progress is visualized on the map. The black line represents the selected search area, and yellow highlight represents area covered. The white ovals are detected phone signals and the corresponding area of uncertainty. Triangles are UAVs, with position error denoted with translucent bubbles. The pink translucent bubble and the icon next to "Drone C" denotes a position error. (B) The mission timeline shows a chronological order of relevant events. (C) System alerts are sorted into two levels: urgent (red) and non-urgent (gray).



	A	B	C	D	E	📶
A		📻	4G	N/A	N/A	4G
B			📻	N/A	N/A	📻
C				N/A	N/A	3G
D					4G	4G
E						📻

A GPS On | last fix **5 min ago** ✓
B GPS On | last fix **3 min ago** ✓
C GPS Off | last fix **15 min ago** ✗
D GPS On | last fix **4 min ago** ✓
E GPS On | last fix **6 min ago** ✓

	GPS Fix (min)	Position Error (m)	Heading Error (°)	Δ Comms Dist (m)
A	On, 5min	4.00m	5°	3.97m
B	On, 3min	1.27m	-3°	1.50m
C	Off, 15min	50.39m	25°	47.29m
D	On, 4min	2.33m	-2°	3.10m
E	On, 6min	5.24m	4°	5.29m

Influence Vectors
Battery ☑
Comms ☑
Phone Signal ☑
Points of Interest ☑
Include in phone triangulation ☑
Call Back Drone

Figure 4. Insets of interface elements from the right screen of Figure 2. (A) Communications connectivity shows (left) the primary view of constellation connectivity with the strongest sending and receiving UAVs, and type of connection, and (right) a more detailed grid of all available communications. (B) Position information gives (left) a primary view of GPS status for the constellation, with a red cross indicating large position uncertainty due to GPS being offline or long time since last fix, and (right) a grid view with lower-level information on UAV position, with time since last GPS fix, position error, heading error, and difference between GPS position and communications calculated distance. (C) Battery power and (D) Altitude per drone over time. (E) Drone heading, position, position uncertainty, and influence vectors. UAVs are re-routed by setting a point of interest using the painter bar or by de-selecting an influence vector so it is no longer used in dynamic co-fields autonomy calculations.

IV. Usability Evaluation Methods

The prototype user interfaces were evaluated by two cohorts, one focused on search and rescue and one on general usability principles. Field personnel from the UVA chapter of the Blue Ridge Mountain Rescue Group (n=2) evaluated the interface for efficacy in monitoring mission progress and error handling through autonomy. The search and rescue personnel were given seven tasks to complete. Users were first provided situational context and introduced to informational elements unique to the interface. The required tasks: 1) Add a mission, 2) Identify phone signals, 3) Explore UAV position issue, 4) Call back UAV, 5) Address non-target phone signals, 6) Reroute a UAV, and 7) End mission. As users completed the tasks, the number of incorrect actions and the time taken to reach the correct action were recorded. After users completed the tasks, they were provided with a survey to gauge the intuition associated with completing each task and asked to evaluate the interface overall. The evaluations used a 5-point Likert scale. Furthermore, expert heuristic evaluators were given the same tasks to complete, but after completing the task were asked to provide feedback on four themes of tracking uncertainty overtime, multiple levels of abstraction, asset monitoring, mission management.

RESULTS AND DISCUSSION

The tasks where search and rescue participants had the most trouble regarded addressing position errors and hiding found phone signals. It should be noted that the tasks with the most steps required to complete were task 1 and 6. As for the expert heuristic evaluators, this cohort required more hints than the first, and had trouble starting a mission, addressing position errors, and adding a waypoint. In regards to tracking uncertainty, the evaluators felt they could accurately track the phone signals' locations, except they did not know if a position error of a drone could be affecting the phone signals location. For multiple levels of abstraction, the evaluators both felt that high level and low-level details related to each other and were accurately displayed, but one wished the alerts could be "clickable" which leads you to more detailed information regarding it. Both evaluators found no issues with asset monitoring. In relation to asset control, both evaluators thought that having one screen dedicated to viewing the mission status and one dedicated to making changes to the mission was easy to follow. But, one evaluator noted it would be helpful to be able to filter alerts and mission status by a certain time window.

Usability & Fit to SAR Process

Tasks 2 and 3 were user evaluation tasks that focused on determining position uncertainty for the phone signals and drones respectively. The interface adequately displayed position uncertainty as shown in section 1 of Figure 2. The usability cohort was generally able to correctly identify phone signal uncertainty, while some encountered difficulty identifying drone uncertainty. Regarding drone uncertainty, evaluators were unsure how to address the displayed uncertainties. Others were unclear if the position uncertainties at either the drone or phone signal level were connected. Future research should focus on improving clarity regarding the alert system and dependencies between phone signals and drone uncertainty.

Understandability & Trust in Automation

The interface worked well with asset monitoring in the evaluation cohorts as users were able to identify the key features shown in Figure 4. The usability cohort determined that the multiple levels of abstraction shown in these features had related information but the overall understandability of this information was not directly tested. When tasked with position issues, users had trouble addressing these errors indicating this information was not completely understandable and placed a higher cognitive load on the user.

Design Implications and Future Work

User evaluation tasks associated with asset control were tasks 4 and 6, where users were asked to call back a UAV and reroute a UAV, respectively. The interface worked well with asset control in the evaluation cohorts as users were able to identify the key features shown in Figure 4. The usability cohort agreed that dedicating one screen to asset monitoring and asset control made sense. By also seeing mid- and low-levels of information on assets, users were able to better understand the actions of the distributed constellation and thus make high-level interventions to control assets. Overall, the autonomy and high-level asset control of the interface allow operators to successfully address non-nominal situations.

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