Drone Swarms in Forest Firefighting: A Local Development Case Study of Multi-Level Human-Swarm Interaction

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ABSTRACT

Swarms of autonomous and coordinating Unmanned Aerial Vehicles (UAVs) are rapidly being developed to enable simultaneous control of multiple UAVs. In the field of Human-Swarm Interaction (HSI), researchers develop and study swarm algorithms and various means of control and evaluate their cognitive and task performance. There is, however, a lack of research describing how UAV swarms will fit into future real-world domain contexts. To remedy this, this paper describes a case study conducted within the community of firefighters, more precisely two Swedish fire departments that regularly deploy UAVs in fire responses. Based on an initial description of how their UAVs are used in a forest firefighting context, participating UAV operators and unit commanders envisioned a scenario that showed how the swarm and its capabilities could be utilized given the constraints and requirements of a forest firefighting mission. Based on this swarm scenario description we developed a swarm interaction model that describes how the operators' interaction traverses multiple levels ranging from the entire swarm, via subswarms and individual UAVs, to specific sensors and equipment carried by the UAVs. The results suggest that human-in-the-loop simulation studies need to enable interaction across multiple swarm levels as this interaction may exert additional cognitive strain on the human operator.

CCS CONCEPTS

• **Human-centered computing** → Human computer interaction (HCI); HCI theory, concepts and models; Interaction design; Interaction design process and methods; User centered design; • **Applied computing** → Computers in other domains.

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KEYWORDS

Human-Swarm Interaction, Swarm applications, UAV swarm, Firefighting drones

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1 THE SETTING

The rapid development of Unmanned Aerial Vehicles (UAVs, or *drones*) in the 21st century has transformed several aspects of society. Journalism, law enforcement, and military operations are but a few example domains where UAVs have become integrated and essential tools [2]. A projected next step in the evolution of UAV systems and their applications is to enable pilots to deploy and control multiple UAVs simultaneously [11]. A fundamental challenge in this effort has to do with control complexity, or the mental effort required by the operator to maintain control of the system. Given that the UAVs requires equal amounts of attention and operate independently of each other, the required mental workload can be described as a linear function of the number of UAVs. In situations where the UAVs are more interdependent and tightly coupled, the increase in workload imposed by each additional UAV follows a greater than linear trajectory [11]. In both cases the mental effort required to control the system will eventually exceed the mental capacity of the operator. Furthermore, various domain-specific contextual demands can require the operator to control heterogenous UAVs – drones of different kinds with different capabilities. Endowing UAVs with autonomy in terms of flight control or higher-order functions – like path planning or decision making – only partially solves these problems.

A promising approach to cope with this limitation is to take a holistic view of the UAV system and control the UAVs as a group using means of control that are not affected by group size [11]. In such a system, the UAVs must be capable of autonomous flight, decision-making, and coordination. These multi-UAV systems are colloquially referred to as *swarms*. UAVs in the swarm coordinate their behavior by adhering to interaction rules based on the internal state of the UAV itself and local environmental and social information, such as the presence of other UAVs [10]. In this way, the swarm is a self-organizing system: its global behavior is not explicitly defined, but emerges from the local interactions between the individual components [10]. This swarming behavior has several desirable properties: it is scalable in the sense that it enables the UAV operator to treat the entire swarm as a single entity; its decentralized organization makes it robust to failure in (or loss of) individual UAVs; it adapts to internal and environmental changes to find new ways to achieve a given goal [10, 19]; and it is cost-effective because its simplicity enables (comparatively) cheap individual components to perform the same functional task as a single complex, expensive UAV [3].

The potential benefits of swarm technology have sparked discussion and research regarding how UAV swarms can be used. Area exploration and surveillance, search and rescue, military point defense, and relaying communications are recurring use case examples listed in the literature [7, 10]. These are examples of general or strategic level swarm applications. Swarm research on the operational level can focus on different things, such as the technical challenges of making multiple UAVs operate and coordinate to solve tasks of varying complexity. Furthermore, in the emerging field of Human-Swarm Interaction (HSI), researchers study the human factors involved in successfully managing multiple (swarming) UAVs and explore different means of interacting with or controlling the swarm.

Because swarm technology is still in its infancy, the vast majority of HSI research is simulation-based. In human-in-the-loop experiments, participants are often tasked with carrying out isolated swarm missions using different interfaces or control methods that are later compared in terms of usability or performance. This line of research is admirable and important in many respects, but it largely fails to account for the context in which the swarm is intended to be used. There is a risk, therefore, that design recommendations for interfaces and for means of control, or the fundamental capabilities of swarms are not entirely appropriate for deployment in the real world.

The goal of this paper is to present a UAV swarm application scenario that takes the contextual needs, goals, and responsibilities of the swarm operator into account. We chose a forest firefighting setting for our scenario of interest because several Swedish fire departments are already deploying UAVs in fire responses, and because such a scenario highlights research challenges for HSI. In a series of workshops with two Swedish fire departments, participant UAV operators described how they work in such a scenario, what their tasks entails, and discussed how they would make use of a hypothetical UAV swarm to manage a forest fire. The scenario is therefore an envisioned description of a swarm system in use told from the perspective of the people who would be tasked with managing it. The scenario is complex, dynamic, and demanding enough to expose contextual demands on human-swarm interaction that can be used to inform the development of UAV swarm technology.

In the following sub-sections, we will provide an overview of the existing literature on firefighting swarms and discuss the inherent difficulty in designing first-of-a-kind systems.

1.1 HSI Research and Firefighting Swarms

Forest fire fighting has previously been identified as a suitable domain for UAVs and other swarm systems, and the technological feasibility of firefighting swarms has been explored in several studies. Martínez-de-Dios et al. [14] demonstrated a multi-UAV system where autonomous and teleoperated UAVs were used in cooperation to detect, confirm, and localize fires and monitor the developing fire front using multi-spectral sensor information. The UAVs were heterogenous in terms of level of autonomy, physical construction and capabilities, and sensor payloads. Although control of the multi-UAV system was highly centralized, the study showed how heterogenous UAVs can be combined to provide valuable information to firefighters. Howden and Hendtlass [8] developed an algorithm for swarming UAVs based on stigmergic fields – digital pheromones – and showed how it could be used to thoroughly survey an area for wildfires. In a similar vein, Pham et al. [18] described an algorithm that makes a UAV swarm track a fire front while maintaining a safe distance to the fire itself and other UAVs. These – and other similar studies – show promising results, but it remains unclear how human operators would interact with such systems to complete real-world tasks. To our knowledge, the only HSI study grounded in an existing operational environment is by Naghsh et al. [16] who present a swarm system of ground-moving robots to support firefighters during search and rescue missions in smoke-filled buildings. The robot swarm is supervised by a remote operator who can issue general commands to the entire swarm or take manual control of any number of robots. However, the study is primarily focused on the interactions between the robots and the firefighters on the ground rather than the remote operator, hence the robot-operator interaction is not extensively described.

As far as we are aware, there are no UAV swarms in active operation anywhere, regardless of domain.

1.2 The Problem of Designing Novel Interactive Systems

Any new technology (e.g. swarms), when applied to an existing work domain (e.g. firefighting), will inevitably change the nature of that work domain, often in surprising or otherwise unintended ways. These changes can significantly alter work routines and activities such that the newly developed technology no longer meets the requirements of the activities for which it was designed. This can result in new and unforeseen potential hazards or points of failure, and the expertise required by practitioners to maintain safe operation can also change. So how can designers and researchers study and design for the cognitive effects of technologies that do not yet exist? This is the *envisioned world problem* [5, 20], which has four distinctive characteristics [20]: Firstly, there is a *plurality* of envisioned worlds since practitioners, stakeholders, and designers all have different visions and motivations. Secondly, each envisioned concept is *underspecified* and vague, only representing portions of the finalized novel work domain. Thirdly, envisioned concepts can be *ungrounded* and disconnected from – even directly contradicting – empirical data about their cognitive and practical effects. Finally, advocates of any given envisioned concept can become *overconfident* in their belief that its list of predicted consequences is complete and accurate.

Several approaches have been suggested to tackle the envisioned world problem. Ethnographic methods and participatory design are two examples of techniques that are recommended because they generate valid and useful data early in the development process, such as insights regarding complicating factors that must be considered [5, 20]. Prototype-driven scenario exploration can also be an option [20]. Walkthroughs and simulations of scenarios that capture the fundamental cognitive demands of the work domain have also been used to deal with the envisioned world problem. In such a setup, an initial scenario configuration can be prepared for participants and various system-perturbing events can later be introduced to create problem-solving situations in the envisioned work setting [20]. This specific approach has been applied to develop Air Traffic Control (ATC) systems [5]. Researchers have also used Cognitive Work Analysis (CWA) – which traditionally requires an existing system to analyze – to design first-of-a-kind systems. For instance, Lundberg et al. [12, 13] combined CWA with conceptual design in the development of an Unmanned Traffic Management (UTM) system to monitor and control UAV traffic in urban environments. Miller and Feigh [15] provide a case study of how CWA was used to develop a Decision Support System (DSS) for human spaceflight operations.

Miller and Feigh [15] also elaborate on the theoretical nature of the envisioned world problem itself by describing how the trajectory from a current and existing technological work domain state (A) to an envisioned future state (B) can follow two different paths. First, the *technology-driven path* involves developing new technologies and deploying them in a work environment. However, this approach is susceptible to precisely the pitfalls that the envisioned world problem entails: practitioners will adapt their work habits to compensate for the presence of the newly introduced technology and its potential deficiencies [15]. In contrast, the *work-driven path* involves focusing instead on extending the tasks and goals of the current domain state into the future. Problems, constraints, expectations, and other attributes of the current domain state are assumed to also be present in the envisioned future but influenced and therefore changed by the hypothesized technology. In other words, this path involves establishing a future work *context* derived from the current work domain [15]. A benefit of this approach is that it highlights required and desirable features of the technology to be developed, and potential mismatches between the capabilities of existing technology and the requirements of the future work domain [15].

Thus far, it seems that the HSI field has leaned towards the technology-driven path. HSI work from a cognitive ergonomics perspective is still 1) underrepresented when compared to computer engineering research, and 2) largely concerned with isolated phenomena pertaining to swarm control and performance while still following the technology-driven path by exploring, developing, and optimizing different swarm interaction methods. There is an apparent lack of HSI research from the work-driven perspective.

2 THE PROCESS

To explore how UAV swarms could be used in a future forest firefighting work context, a series of workshops were conducted with participants from two Swedish fire departments that regularly deploys UAVs in fire responses. Invitations to participate in the study were sent via email to individuals previously known to be part of the UAV unit of each fire department. These individuals put together a list of suitable participants and invited them to the workshops. The participants themselves had mixed backgrounds: in total, there were three unit commanders and five firefighters with UAV operation training. The participants were aged 23–43 years (M = 34.33, SD = 7.20), had an average of 10.7 years (SD = 6.19) of work experience as unit commanders or firefighters, and the UAV operators all had approximately a year's worth of professional flying experience. One unit commander and one firefighter participated in the first workshop, and the rest participated in the second.

The two workshops followed the same outline. After the participants had provided their written informed consent, the workshop leaders gave a short presentation to present the study's background and purpose. Furthermore, participants were introduced to the basic concept of UAV swarms (e.g. their composition and emergent behavior), the purpose of this being to stir their imagination and further enable them to discuss and reason about swarms in their work context.

The workshop activity itself was divided into two phases. First, participants were asked to describe – from start to finish – their workflow during a typical forest fire response, including decision points, information needs, and general activities, with special attention being given to the use of the UAV. To do this, participant groups were given printed 1:9200 scale maps of a Swedish rural village area, sharpies, and 8 mm^3 plastic cubes in black, blue, red, and yellow colors to represent UAVs, firetrucks, or whatever else the participants required to explain the scenario. As the participants explained how they would approach a forest fire setting, the workshop leaders kept fieldnotes of the phases of work and activities being described by the participants.

In the second workshop phase, participants were asked to assume they had access to a heterogenous UAV swarm (consisting of UAVs carrying visual spectrum cameras and infrared (IR) cameras, search lights, and other payload modules), and to explore and describe how they would utilize it to combat the same forest fire they had previously created in phase one. Notes were taken in the same way as before, focusing on work phases, tasks, and activities to construct a step-by-step description of the scenario.

Each workshop phase lasted for roughly 90 minutes, with a 15-minute break in-between. Both workshops were video and audio recorded by two tripod-mounted cameras angled towards the printed maps, with two handheld voice recorders placed on the table for audio backup. The recorded video material was analyzed in relation to the formatted swarm scenario to see how the participants used the plastic cubes (representing the UAVs) in each scenario step. Specifically, we were interested in how they placed and interacted with the cubes while explaining how they envisioned the UAV swarm to be used in the future.

Synthesizing the swarm scenarios created by each workshop group into one coherent scenario turned out to be a straightforward process. The plan was to work together with the second workshop group to compare the two scenario descriptions, identifying their differences and commonalities, and merge them into one. During the second workshop, however, it became apparent that the two scenarios were very similar in terms of workflow, task descriptions, and overall vision. The two swarm scenarios were merged into one by comparing and analyzing field notes and reviewing the video recordings.

3 FINDINGS

The following subsections will cover the workshop results, starting with a description of the current UAV operations of the participating fire departments. This is then contrasted with the envisioned swarm scenario for forest firefighting. We then present a generalized model of the human-swarm interaction extracted from the swarm scenario description.

3.1 Current Single UAV Implementation and Use

To provide a backdrop for the swarm scenario we will begin by explaining the single-UAV forest fire scenario created in phase one of the workshops. This was synthesized and constructed in much the same way as the swarm scenario, as described above. As both fire departments are still experimenting with how to use the UAV, this scenario is based both on how they currently operate and their short-term implementation plans.

When called to action, UAV operators determines whether the response area is within a restricted flight zone and, if so, notifies the appropriate ATC of their intention to fly the UAV. Once at the scene, the UAV is launched and used to gain an overview of the area. First, the exact location and size of the fire is determined. Next, using the UAVs visual spectrum camera, the operator searches the nearby area for access roads to get the firetrucks as close to the fire as possible. Also, terrain features such as water sources, natural barriers (e.g. rivers or power cable clearings), buildings, and other infrastructure are identified. The operator and area commander then assess how the fire will spread and make a preliminary threat analysis. The area commander then formulates a plan for how to deal with the fire.

When the entire force is busy fighting the flames, the operator stays close to the commander to maintain effective communication. A live video feed from the UAV can also be sent to an off-site commander to coordinate larger efforts. The UAV is used to maintain an overhead view of the mission area, to look for additional fires (by looking for plumes of smoke), and to keep firefighters on the ground out of harm's way. Furthermore, if the firefighters lack GPS trackers, they can coordinate with the operator via radio to move the UAV directly overhead of their position, using the UAV as a visual indicator of where extra resources are needed. The UAV is generally kept upstream of any smoke plumes because they obscure visibility, although the IR camera can be used to see through the smoke. Additionally, unless a continuous visual feed is required or the UAV is needed for other tasks, it is landed and only used to update the overhead view every 10–15 minutes, conserving energy. If the Ground Control System (GCS) is alerted of any incoming aircraft, the operator immediately lands the UAV.

Finally, when demobilizing after the main fire has been extinguished, the UAVs visual spectrum camera continues to look for smoke and its IR camera is used to look for smoldering patches on the ground. This can be done autonomously by selecting an area and instruct the UAV to systematically survey it for spots in excess of a set maximum temperature, marking hotspots on a map and alerting the pilot. Targeted efforts to put out these hotspots using only minimal manpower saves time and resources.

3.2 Envisioned UAV Swarm Implementation

Now we will present the envisioned swarm scenario created from the two workshops. The workshop participants described two ways in which a wildfire scenario could start. First, they could be called in by an emergency operator, in which case they imagine deploying a fast UAV from the station (e.g. a fixed-wing drone) to the reported area to quickly get an initial overview. Second, they described how they could use a swarm to survey a known high-risk area in dry seasons. The swarm would fan out to form a straight line, several kilometers in length, and systematically sweep the selected area for fires, using both visual spectrum and IR sensors. Whenever a UAV identifies a potential fire it brings in additional UAVs to verify the sighting, with the rest of the swarm reorganizing to close the gaps left by the UAVs that have now stayed behind. During its sweep the swarm also collects topographic data to update maps with access roads, water sources, and other relevant information which cuts down on response times.

When ground units arrive, the swarm is given multiple tasks. It must provide a good view of the main fire while continuously look for secondary fire locations. It is also tasked with tracking and supporting the ground units, e.g. by providing a birds-eye view of their work area to prevent them being surrounded by the fire, assisting with flashlights for when working in the dark, or by delivering food and other supplies.

The participants also envisioned how a swarm could be used to actively fight the fire. Large helicopter UAVs collects water from nearby lakes or rivers in a collapsible bucket slung (i.e. a Bambi bucket), and selectively drops it in designated areas (see [6] for a similar use case). The operator uses, for instance, a touchscreen tablet to draw a line on the map, and the water-UAVs proceeds to drop water along that line. Alternatively, the water-UAVs use their own visual spectrum and IR sensors to autonomously locate fires in a designated search area or cooperate with scouting UAVs. Scouting UAVs also searches the area for civilians and use loudspeakers and warning lights to instruct them to evacuate. However, this functionality could be more useful in other parts of the world where a hotter and drier climate makes evacuation efforts as important as fighting the fires themselves. The loudspeakers can also be used by a swarm operator to communicate directly with civilians or ground units. Furthermore, the water-UAVs primarily fights the fire downwind, leaving the less intense tail-end to ground units, and tries to work their way around towards the back. The swarm use the ground units' GPS position and IR sensor data to make sure not to drop water directly on top of them.

The water-UAVs and scouting UAVs are used during mop-up in much the same way as previously described. The swarm uses IR sensors to search the area and directs water-UAVs to drop water on any hotspots or send GPS coordinates to ground units for targeted extinguishing missions. Ground units manually inspects the area to confirm that the area is clear. A small swarm of scouting UAVs

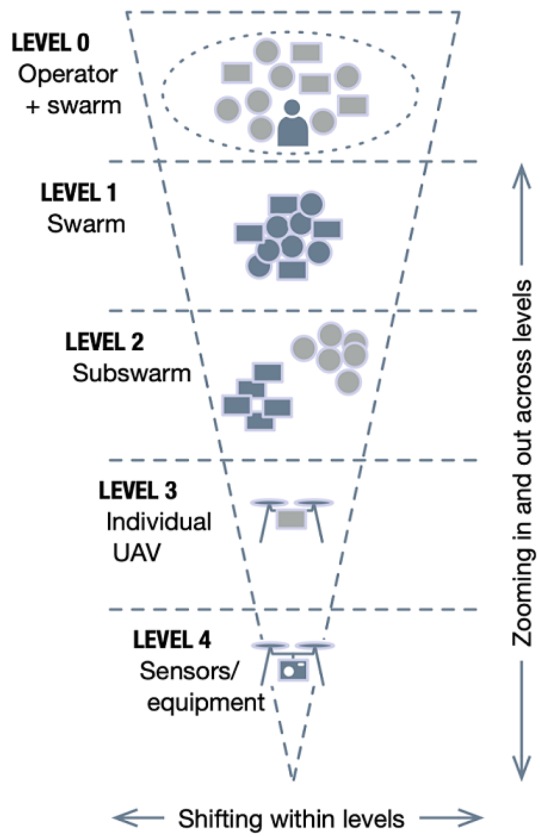

Figure 1: The Swarm Interaction Model.

are left behind to sweep the area for several days or weeks to track if the fire reignites.

3.3 Traversing System Levels in Swarm Interactions

Based on the swarm scenario detailed above and reviewing video recordings of the workshops we have created a model that describes how the swarm operator interacts with the system. The model, shown in Figure 1, illustrates how the operator interacts with four different system levels: the swarm level, the subswarm level, the single UAV level, and the payload level. The operator and UAV swarm can also be described as a joint cognitive system with which the unit commander interacts in different ways. However, this interaction, denoted as *Level 0* in Figure 1, was of peripheral relevance to the current study. Switching between interacting with these different levels is represented in the model as vertical movement entailing zooming in and zooming out between overall situation and details. Additionally, the interaction can involve lateral movement, or panning, within levels.

The first level, *Level 1*, represents the entire swarm. In this level of interaction, the operator is mainly concerned with navigating the swarm to a general location, assigning global missions, and monitoring global system information. Figure 2 shows how the swarm

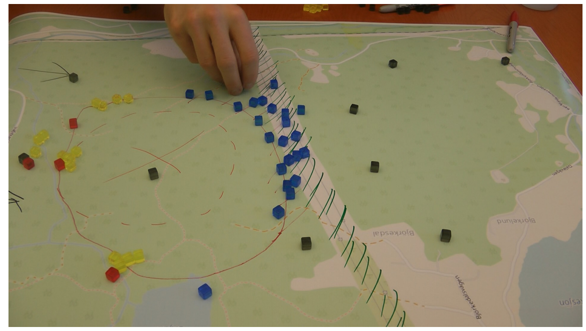

Figure 2: Swarm-level interaction (Level 1) to maintain a general overview of the mission area.

is used to monitor and engage the entire mission area. Black cubes represent scout UAVs, blue cubes represent water-UAVs, and red and yellow cubes represent fire trucks and fire fighters, respectively. The fire itself is drawn as a red circle. Notice how the water-UAVs are focused on the fire front downwind, leaving the less intense trailing end to ground forces. Lateral movement within this level involves deflecting attention away from the swarm itself to focus on some other task like communicating with fire fighters or the unit commander.

In *Level 2*, the operator interacts with multiple subswarms. These can be created in several ways. In a heterogenous swarm, each set of UAV models could be treated as a subswarm (or aggregate agent), their independence from each other determined by contextual factors like mission requirements or complementary feature sets. Subswarms can also be the result of the swarm self-organizing to carry out multiple tasks assigned by the operator, or to deal with a single task. Also, the operator can define geographical areas and let the swarm autonomously allocate area-specific responsibilities between UAVs, forming subswarms in the process. The operator can also create subswarms by explicitly selecting several UAVs and give them a specific assignment. An example is shown in Figure 3 where the operator tasks a subset of UAVs carrying headlamp modules (black cubes) with lighting the way for fire fighters (yellow cubes) on the ground to maintain efforts during the night. Simultaneously, the water-UAVs and other scout UAVs carry on with their existing tasks so the operator must split his or her attention between the subswarms, exemplifying lateral movement within this level of the model.

The third level, *Level 3*, is about interacting with a single individual UAV much like the current activities of the UAV pilots. The operator can assign special tasks to a UAV, like scouting a specific area, and assume manual flight control to perform mission critical or otherwise delicate tasks. A key difference, however, is the added information needs inherited from the other levels. The operator still requires information about what the rest of the swarm is doing. Lateral movement within this level implies switching between different individual component UAVs, conceivably to perform multiple sequential tasks.

Finally, *Level 4* concerns the interaction with cameras, sensors, communication and networking equipment, system diagnostic tools, or cargo available to the swarm and its constituent UAVs.

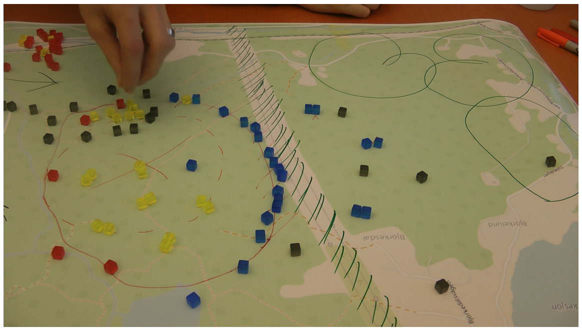

Figure 3: Subswarm-level (Level 2) interaction focusing on UAVs carrying flashlights (black cubes) to support firefighters (yellow cubes).

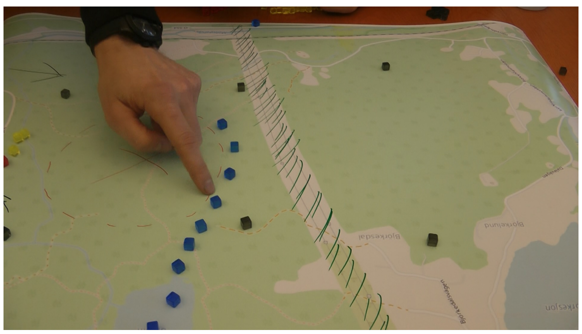

Figure 4: Detailed control of where UAV cargo (water) should be dropped (Level 4).

Figure 4 shows an example where the operator would pinpoint a small area, such as specific IR hotspots, and instruct an individual water-UAV to drop its water load on that target. Another example would be to switch from visual spectrum cameras to IR cameras, either globally or for a single UAV, to monitor or search an area.

4 DISCUSSION

The swarm interaction model, when applied to the workshop swarm scenario, has several important research implications for HSI. It suggests that there is more to human-swarm interaction than what has previously been explored in the literature. Broadly speaking, HSI studies are mainly (and explicitly) concerned with *Level 1* (swarm) or *Level 2* (subswarm) of the model while focusing on issues of swarm command and control [1, 4, 9] and/or human factors like mental workload and situation awareness [6, 17]. However, the single-UAV level, *Level 3*, is not typically explored in the HSI field. As the current results show, this forfeits the opportunity to study the cognitive implications of having to keep track of the rest of the swarm while attending to an individual UAV. In a real-world setting an operator would not solely interact with any single system level but continuously traverse the system levels as the mission develops. It may therefore be beneficial to include the individual agent level in HSI studies to explore and ultimately understand its unique challenges and possibilities in the context of the swarm.

Another observation is that the payload level, *Level 4*, is continuously involved in a way that the other levels are not: whereas the operator must interact sequentially with the entire swarm, its derivative subswarms, or any one of the individual UAVs, the operator *always* interacts with *Level 4* in one way or another, be it actively (e.g. switching cameras) or passively (e.g. perceiving the positions of UAVs or fire hotspots). Furthermore, this *Level 4* interaction is parallel to the traversal between the first three levels in the sense that the operator can – in theory – switch from the visible spectrum camera to the IR camera regardless of whether they are currently controlling the swarm, a subswarm, or a single UAV. In other words, controlling and supervising the swarm is about information management: the operator's job is to collect information using the cameras and sensors carried by the UAVs in the swarm and act upon this information in different ways, like sharing it with the unit commander or deciding where next to navigate the swarm. In this perspective, the payload – i.e. cameras, sensors, or other cargo – is what's important to the operator and the mission, meaning that the swarm can be viewed as a means of positioning cameras and sensors where they need to be. This suggests that HSI design research opportunities includes making the swarm itself transparent to the operator, focusing instead on the flow and visualization of the information collected by the swarm.

The swarm interaction model itself represents what Dekker and Woods [5] describe as an effort to understand what modes and levels of interaction will be meaningful and relevant to practitioners in the future domain setting. Such insights are important for system design since operators may wish – or be required – to switch between taking detailed control over select portions of the activity on the one hand, and apply general control or course correction on the other [5]. Our swarm interaction model thus offers insights regarding future work domain contexts along the work-driven path [15] and can save valuable time and resources when considered early in the system development process.

This study makes an important contribution to the HSI community in showing how future UAV swarms can potentially be used and interacted with. However, the results are limited to a single domain, in this case forest firefighting. Although the swarm interaction model is a generalized representation of this, it would certainly benefit from additional data in other domains. We believe that the workshops represent an appropriate method given the goals and resources available for data collection. They provided an interactive and creative setting for the participants to share their expertise and envisioned concepts. Alternatively, a more traditional ethnographic observation phase could have been included at an early stage to gain a basic understanding of the domain, however the irregular occurrence of forest fires (or structured training sessions) made this an unfeasible approach.

5 CONCLUSION AND WHAT IS NEXT

HSI is still a young and emerging discipline that is focused on a fascinating, promising, and rapidly advancing technology. Even though good and important research is being done, the field as a whole seems to put the proverbial cart before the horse by developing swarm technology at a blistering pace without considering how it all fits into an actual work domain setting. This mistake has been repeated throughout history, resulting in practitioners under-utilizing or actively rejecting new technology in their respective domains [15]. To avoid this, the HSI field must also consider what future contextual factors and affordances are likely to affect how the envisioned technology will be received and used.

This study shows that human interaction with – and control of – autonomous UAV swarms happens in and between multiple interconnected levels in a dynamic way, as represented in the swarm interaction model. We argue that an important challenge for the HSI community is to understand how to design for effective, efficient, and resilient human-swarm interaction with this in consideration. We further believe that cognitive ergonomics researchers – in partnership with industry practitioners and end-users – have an important role to play in this effort.

The swarm interaction model presented in this paper highlights the need for integrated research on human-swarm interaction. However, it cannot – in this first iteration – explain the underlying mechanisms and dynamics that triggers the traversal from one level to another. Future studies should consider using structured cognitive analytical methods (like CWA) or state diagram modeling techniques to further develop the model in this respect. The swarm interaction model, in its current or future iteration, can be used to appropriately design and simulate various domain tasks where natural and structured level traversal can be observed and studied. This is an important step on the path to develop and deploy UAV swarms in the real world.

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