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Human-Swarm Partnerships: A Systematic Review of Human Factors Literature

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ABSTRACT

It is widely recognised that multiple autonomous agents operating together as part of a team, or swarm, could be used to assist in a variety of situations including search and rescue missions, warehouse operations and a number of military scenarios. From a sociotechnical perspective, these scenarios depict situations in which non-human and human agents are likely to work together in order to achieve a common goal. Despite this, there has been some concern that Human Factors research into human-swarm partnerships is lacking. Thus, in order to understand the current 'state of the art', a systematic literature review was conducted to explore what Human Factors research is being conducted within the area of human-swarm partnerships and explore what design guidance exists to support the development of efficient and effective relationships. The review revealed five key research themes: interaction strategies, user interface design, management, operator monitoring and trust. However, when it comes to design guidance, there is very little available. One potential avenue for future research centre on the concepts of Meaningful Human Control and Effective Human Control. These concepts have been recognised as providing the foundation in which the design of human-swarm partnerships may be developed. Using the principles of Systems Theory, it may become possible to shape a systems architecture, thus ensuring that Human Factors are considered early on in the product development lifecycle.

Keywords: Human-machine interaction, Human-machine team, Human-swarm interaction, multi-agent system

INTRODUCTION

Unmanned Aerial Vehicles (UAVs) are often viewed as a convenient and cost effective way to gather information that is not easily accessible from any other means (Hildmann et al., 2019). However, we are beginning to see increasing efforts to scale up the autonomy of single-UAV systems to create aerial swarms (Macchini et al., 2021). It is thought that aerial swarms may be used to assist in various situations including search and rescue missions, warehouse operations and military scenarios (Schranz et al., 2020). Compared to a single robot, a swarm can provide a more efficient means to cover large areas and are scalable (i.e., can easily add or remove individual robots without significantly impacting the performance of the remaining group) (Bales & Kong, 2017). Brambilla et al., (2013) propose that swarm robotics is based on the following principles: robots are autonomous, are situated in the environment and can adapt their behaviour to modify it, have local sensing and communication capabilities, do not have access to centralised control or global knowledge and can cooperate to fulfil a mission. However, there are other branches of swarm robotics that will preserve the role of the human operator (both in terms of operation and supervision) (e.g., Hocraffer & Nam, 2017). In such contexts, the role of the human operator will remain integral to the success of such systems (Dousse et al., 2016). Human-swarm interaction therefore falls between the fields of 'swarm robotics' and 'human factors' with one focussing on the technical and one focussing on the operator. Each of these fields is integral to the success of human-swarm partnerships. However, Clark et al., (2022) caution that human factors research into the field of swarm robotics is limited despite the growing interest in how we can best design efficient and effective human-swarm partnerships. To further understand the constraints and limitations of research into this area, this paper aims to consolidate the research available on human-swarm partnerships through means of a systematic literature review. This review intends to address the following research questions:

- RQ1: What Human Factors research is being conducted within the area of human-swarm partnerships?
- RQ2: What design guidance exists for efficient and effective relationships between human operators and robots?

APPROACH

A systematic literature review was conducted using Scopus, Web of Science and Google Scholar using the following search terms;

> *("Human swarm interaction" OR "human swarm team" OR "human swarm partnership") AND ("drone" OR "unmanned aerial vehicle" OR "uav" OR "unmanned aircraft system" OR "uas" OR "remotely piloted aircraft")*

Searches from Google Scholar were limited to the first 100 articles. The initial search returned 143 articles. Duplicates were first removed and then the screening process involved filtering articles by titles then by abstract and then finally, full text. This approach led to 55 articles being retained.

FINDINGS

RQ1: What Human Factors research is being conducted within the area of human-swarm partnerships?

Inductive coding was used to identify themes within the retained text. This was done in an effort to provide greater insight into the current focus of research with the context of human-swarm partnerships. A total of 5 themes were identified: interaction strategies, user interface design, management, operator monitoring and trust (see Table 1).

Table 1. Themes and descriptions.

Theme	Sub-theme	Description
Interaction Strategies	N/A	Papers that make reference to, or explore the use of, direct interfaces (i.e., natural human pose).
User Interface Design	N/A	Papers that explore the design of traditional human-computer interfaces.
Management	Roles	Papers that discuss or identify different agent roles within human-swarm teams.
	Automation	Papers that discuss the impact of automation on human-swarm partnerships.
	Control	Papers that discuss control frameworks relevant to the discussion of human-swarm partnerships (e.g., meaningful human control / effective human control).
Operator Monitoring	N/A	Papers that make reference to, or explore the use of, different physiological assessment measures.
Trust	N/A	Papers that explore the concept of trust within human-swarm partnerships.

Interaction Strategies

A key consideration relating to human-swarm partnerships is the method of interaction. Kolling et al., (2013) discuss interaction from the perspective of "when" interactions may occur whilst others focus more on "how" interactions. However, the literature review predominantly found articles focussing on "how" interaction may occur (n = 11). Of these, 5 papers focussed on gesture-based interaction, 2 focussed on tactile-based interaction, and the remainder explored some combination of interaction strategies. Whilst voice commands have previously been found to improve an operators ability to control subsystems (e.g., Draper et al., 2003, cited by Couture et al., (2017), technological advances have enabled new modes of interaction (e.g., gesture based command modes, the use of tactile interfaces). The rise of Body-Machine Interfaces (Agishev et al., 2019; Macchini et al., 2021) provides a mechanism in which human awareness can be augmented when visual feedback alone is not sufficient to enable reliable control.

Ferrer (2018) argues that gestures, head and body movements are a natural way for human operators to communicate their intentions and/or strengthen messages. Hand gestures in particular have been utilised within human-robot interaction although we must not underestimate the challenges associated with this. For instance, whilst gestures may be fairly intuitive to other human operators, conveying meaning to a robot, or group of robots, has been particularly challenging (Ferrer, 2018). In addition, the development of gesture taxonomies have typically focussed on remote interactions (i.e., teleoperation). However, teleoperation represents a form of persistent interaction and therefore the utility of gesture for other interaction strategies remains to be established.

User Interface Design

Arguably, whilst the “when” and “how” are important areas of consideration, so too is context. In real-world contexts, swarms may be deployed for surveillance (e.g., Xu & Song, 2021), act as communication relays (e.g., Totten, 2014) and be used to assist in search and rescue operations (e.g., Tanzi et al., 2016). The applicability of direct interfaces is likely to be reduced in such contexts as the emphasis is placed upon the planning of feasible and optimal trajectories, selecting appropriate payloads and the development of real-time algorithms to enable the command and control of multiple unmanned assets simultaneously. A reliance on more traditional human-computer interfaces is therefore anticipated.

Kolling et al., (2013) highlight that whilst some research has been conducted into user interfaces for swarms, many current interface designs and theories relating to human-swarms stem from research on aircraft/helicopter pilots and single UAV operations. However, an aerial swarm creates a much larger amount of data and requires significantly more multitasking than controlling a plane or a single UAV. This is because multiple vehicles must be controlled or supervised at once and the data collected from them may be of different types (visual, infrared, audio, etc.) and from different perspectives. This is likely to place significant workload burdens on human operators and leave them vulnerable to mental fatigue and loss of situation awareness.

Currently, most Ground Control Stations tailor to the control of single UAVs, meaning that typically only a single UAV is controlled and data is fed back to the operator through traditional cockpit-like instruments (Fuchs et al., 2014). For multi-UAV systems, such interfaces are unlikely to be appropriate. Fuchs et al., (2014) explored the use of Ecological Interface Design (EID, Vicente & Rasmussen, 1992), to enhance traditional interfaces so that they can be used to support the management of multi-agent systems. The approach permitted the successful management of four UAVs, however, there was still a requirement to deliver control actions on a singular basis meaning it was labour intensive for operators. Even so, Fuchs et al., (2014) demonstrated that EID promoted creative problem solving to scenarios that could not be solved by following a fixed procedure.

However, the issue of scalability was highlighted by Soorati et al., (2021) who argued that one of the key challenges related to human-swarm interaction was the design of appropriate interfaces that could cater for scalable swarms and enable the user to monitor and control multiple assets. They asked 100 participants to evaluate different human-swarm visualisation methods where 50 drones were represented as either black-point dots or on a density heat map. They found that heat maps are more effective at addressing usability and acceptance issues amongst human operators, perhaps indicating that for scalable swarms, heat maps may provide more efficient means of communication between the human and non-human agents. Overall though, there is a general consensus within the literature that more research is required within this area.

Management

The management of human-swarm partnerships is likely to be extremely complicated. This is because such partnerships will involve multiple subsystems, operating simultaneously to achieve a common goal. One of the key discussion points within the literature appears to be around the role of the human operator within human-swarm partnerships. Where Scholtz et al., (2002) proposed that there are five roles that a human may fulfil, Hussein & Abbass (2018) argue that no strict boundaries exist between the roles of operator, supervisor and peer meaning that they may seamlessly transition between them depending upon the tasks required and their context. Unlike single UAV operations whereby an operator is likely to be in control of manually controlling the movement of the vehicle, in multi-agent systems, operators will need to perform higher-level mission management tasks. With this in mind, operators may transition from being 'in-the-loop' to 'on-the-loop' (and back again), a capability particularly important when we consider that human operators are often viewed as a failsafe to ensure swarm behaviours align with mission objectives (Crandall et al., 2017). Further, Cummings et al., (2013) argues that human agents are often more effective at integrating data from multiple sources, correctly identifying targets of interest and predicting future human actions in comparison to unmanned vehicles. Enabling human control over the swarm therefore provides the opportunity for dynamic authoritative control that is based upon local circumstance and expertise (Naghsh et al., 2008). It also serves to mitigate against potential out-of-the-loop performance issues commonly associated with boredom, fatigue and complacency (i.e., Cummings & Mitchell, 2008). However, prolonged periods of being 'on-the-loop' may increase the risk of transitioning to 'out-of-the-loop'.

It is also widely recognised that the level of automation in which a system operates can impact upon task allocation, division of responsibility and the decision making process. In the context of aerial swarms, control is more likely to be delegated to autonomous navigation algorithms (Macchini et al., 2021) therefore limiting active operator involvement. This means that similar human factors issues that are found in other domains employing increasing levels of autonomy (e.g., traditional aviation, process control, ship navigation) are likely to be observed. These include, but are not limited to, issues related to situation awareness (Endsley, 1995), workload (Parasuraman et al., 2008) and boredom (Cummings et al., 2013). This is because it is the intermediate levels of automation whereby the role of the operator is less well defined and 'partner-like' collaboration is more likely to be expected (Chen & Schulte, 2021).

Even systems categorised as being fully autonomous are rarely human-free in reality. However, the level of human control is mediated by the role in which they assume within the system itself (i.e., there are obvious differences between supervising a swarm of UAVs and manually controlling them). Given that human agents will continue to be involved in swarm management (Hocraffer & Nam, 2017), they must be properly supported in maintaining meaningful human control (Boardman & Butcher, 2019). Typically, the concept of meaningful control is used within ethical, legal and political debates (Santoni de Sio & Van den Hoven, 2018). However, the concept also provides a foundation in which the design of human-swarm partnerships may be developed. Indeed, frameworks for Meaningful Human Control (MHC) have also been explored in the context of automated driving (e.g., Heikoop et al., 2019) and there is no reason why such an approach may not be useful here. MHC is characterised by three components (Horowitz & Scharre, 2015):

1. Human agents have the capacity to make informed, conscious decisions;
2. Human agents have sufficient information about the consequences of their actions and decisions; and
3. Human agents are properly trained to ensure effective control over the swarm.

Essentially, MHC enables the possibility to relinquish some degree of operational control to non-human agents yet maintain overall control via means of system design (Heikoop et al., 2019). Horowitz & Scharre (2015) argue that the components of MHC may be viewed as design principles rather than any specific requirements. Santoni de Sio & Van den Hoven (2018) posit two essential conditions that must be satisfied in order for autonomous systems to remain under MHC. Firstly, a tracking condition states that the system should be able to morally respond to facts within the operational environment. This means that the system should always be able to adjust its behaviour based on the human operators, or designers, intent (Santoni de Sio & Van den Hoven, 2018). Second, autonomous systems should be traceable (i.e., it should be possible to trace back the outcome of operations to a human agent somewhere along the chain of design and/or operation).

However, Hoem et al., (2021) caution that technical reliability and maturity, in addition to the requirements for system transparency and clearly defining operational boundaries remain problematic. High profile accidents within aviation (i.e., Boeing 737 MAX) and driving (i.e., Uber and Tesla) have highlighted the issues associated with overreliance and lack of understanding about the capabilities of a system when it becomes increasingly automated. Hoem et al., (2021) propose that the principles associated with MHC should be used as an input to support the development of system architecture and to verify if the interaction between the system and human agent is appropriate.

Operator Monitoring

A total of five papers were concerned with studying human-swarm interaction performance through means of physiological assessment of human operators. Physiological assessment is thought to provide insight into the level of task demand (e.g., Bales & Kong, 2017), the impact of operator role (i.e., supervisor or tactician) on physiological state (e.g., Manjunatha et al., 2021) and, operator situation awareness (e.g., Rojas et al., 2019). Similar to other domains, such information may be used as a trigger to either redistribute the allocation of tasks to ensure optimal levels of system performance or prompt transition to a more appropriate role (i.e., from 'out-of-the-loop' to ‘on-the-loop’ to ‘in-the-loop’). Lapses to operator situation awareness in the context of human-swarm partnerships may lead to poor human performance as characterised by increased error. It was recognised by Rojas et al., (2019) that one of the major factors that can result in a loss of situation awareness is degraded data transmission. In instances whereby the human operator must interact with robotic swarms (i.e., through means of teleoperation), it is essential that situation awareness remains intact and that operators have access to critical information at appropriate times.

There is a growing body of research exploring the potential utility of real-time indicators of human performance to be used to augment the tasks completed by multi-agent systems.

Trust

Prior research within the area of human-robot interaction has shown that trust is largely mediated by the performance of the robot (Nam et al., 2019). However, trust calibration in the context of swarms is further complicated because task performance may not be readily understandable by the human operators. Nam et al., (2019) argue that human agents tend to make their decisions based on the physical characteristics of a swarm rather than its performance. Even so, it would appear that ‘trust’ mediates the interdependency between automation reliability and human reliance on automation (Liu et al., 2019). In dynamic, real-world environments, the performance of the swarm will be impacted by uncontrollable factors (i.e., wind disturbances) which may lead to undesirable behaviour (Liu et al., 2019). In these instances, there is a risk that human trust in the swarm may be negatively impacted potentially triggering unnecessary human intervention. Inappropriate trust calibration can therefore limit the effectiveness of the human-swarm partnership overall.

RQ2: What Design Guidance Exists for Efficient and Effective Relationships Between Human Operators and Robots?

Given the scarcity of human factors literature within this area, there is limited design guidance on how best to design efficient and effective human-swarm relationships. Research appears to be limited to specific areas or themes. However, the concept of MHC appears to be gaining increasing popularity within the literature. Further research within this area is therefore suggested whilst also recognising that a complimentary component of human control was proposed by Boardman & Butcher (2019). They suggest that ‘Effective Human Control’ (EHC), unlike MHC, emphasises the benefits of human involvement within a system. EHC recognises that human agents can be enablers of performance and risk reduction. Boardman & Butcher (2019) outline that both MHC and EHC should be considered together when considering control management. This means all possible interactions should be considered (e.g., human-human, machine-machine, human-machine, multiple teams). This echoes the principles of following a ‘system of systems’ approach that recognises multiple, interdependent systems are greater than the sum of the individual systems of which it is comprised (e.g., Stanton et al., 2012). In order to support the analysis of interactions occurring between and across different layers of a system, there are a number of methods, founded within systems theory that may be appropriate. These include the Systems Theory Accident Model and Process (STAMP; Leveson, 2004), AcciMap (Rasmussen, 1997), the Event Analysis of Systemic Teamwork (EAST; Stanton et al., 2008) and the Human Factors Analysis Classification System (HFACS; Wiegmann & Shappell, 2017). The benefit of using theoretical models to depict how complex sociotechnical systems may function is that they provide a foundation in which the task, user, and information requirements can be better understood.

DISCUSSION

The findings of this review provide insight into prevalent research themes within the area of human-swarm partnerships. However, the authors acknowledge that this body of research remains largely in its infancy. This means that supporting the role of the human agent within complex multi-agent systems remains an enduring challenge going forward. It is clear that more research is needed to understand how human and non-human agents may work together in order to achieve a common goal.

The preservation of control over a system that is not wholly operated by a human agent represents an important area of human factors and ergonomics research within many domains. It is however particularly relevant in the discussion of human-swarm partnerships as the human agent is likely to play a pivotal role in overall mission success (Crandall et al., 2017; Cummings et al., 2010; Naghsh et al., 2008). The concepts of MHC and EHC (Boardman & Butcher, 2019) provide a potentially interesting area for exploration although Calvert et al., 2020) recognise that Human Factors play a central role in determining the mere definition of 'meaningful'. Horowitz & Scharre (2015) stress that human agents should retain full decisional awareness and possess a comprehensive understanding of the context of action in order for control to be meaningful. This implicates four of the research themes identified as part of this review: interaction strategies, user interface design, management and trust. Operator Monitoring, the final theme identified as part of this review, is indirectly linked to MHC and EHC because it acts as the mechanism in which operator engagement can be augmented. Arguably then, the building blocks to achieve MHC and EHC are beginning to take shape. However, more research is needed to bring this altogether in the quest for efficient and effective relationships between human agents and robot counterparts.

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