A review of human swarm interaction

Jan Carlo Barca
Defence Science and Technology Group, Melbourne, Australia

Article Info

Article history:

Received Jun 11, 2025
Revised Nov 18, 2025
Accepted Feb 9, 2026

Keywords:

Human robot interaction
Human swarm interaction
Multi-robot systems
Review
Swarm robotics

ABSTRACT

A review of recent activities in human swarm interaction (HSI) research is presented in this paper. The paper begins with providing a short description of swarming. It then discusses HSI and explains why it is beneficial to enable human operators to supervise swarms of robots. Then, a wide range of papers, which present novel methods for interacting with swarms of robots, are reviewed. Four control methods that can be used to transmit an operator's intent to a swarm are also discussed. Levels of autonomy and flexible autonomy in HSI are furthermore described. At the end of the paper, a discussion of the gaps in knowledge that still must be filled to enable swarms of robots to operate in the real world is presented. It is suggested that more research into techniques for remote interaction with robotic swarms be conducted. This includes methods that enable remote interaction with swarms of swarms. More work on HSI in degraded communications environments is also required. Additional research into swarm autonomy is furthermore needed to facilitate efficient supervisory control. Lastly, there is room for more work on trust in HSI, as robotic swarms can only be used by humans if they can be trusted.

Corresponding Author:

Jan Carlo Barca
Defence Science and Technology Group
Melbourne, Australia
Email: jan_carlobarca@hotmail.com

1. INTRODUCTION

Robotic swarms consist of autonomous robots that are situated in the environment. These robots have local sensing and communication capabilities, and many researchers state that swarms do not have access to global knowledge or centralized control [1]. However, to enable swarms of robots to solve real-world problems, other researchers want to preserve the role of a human operator [2], which is likely to require some degree of centralization and insights into the global state of the swarm.

There is a range of potential advantages associated with the use of swarms of robots. According to Barca and Sekercioglu [3], swarms can exploit the sensing abilities of large groups. This means that one can discover areas of interest fast, decide if one wants to enter them, and rapidly determine when to leave. Appropriately controlled swarms can furthermore provide superior situational awareness and facilitate higher levels of robustness than systems that solely rely on one individual, as other robots can take over work that previously was conducted by a failed robot. Additional advantages are that swarms can distribute workloads amongst their members to accomplish more significant results and manipulate their environments more efficiently than one individual.

Robotic swarms are generally expected to operate autonomously [4]–[7]; however, the involvement of an operator can be advantageous—or even essential—in real-world applications. The operator can modify mission objectives and ensure that the swarm's behavior remains aligned with the overarching goals of the mission. Additionally, a human operator can provide high-level reasoning in unstructured, dynamic, and complex environments. The operator can also detect and correct system failures or supply out-of-band information that is unavailable to the swarm's sensors. Finally, the operator can assume responsibility for decision-making when the swarm undertakes high-risk tasks. As a result, swarm robotics and HSI are useful in a wide variety of application areas such as sea exploration, search and rescue, space missions, and defense [8]. However, a significant challenge still lies in how one can realize meaningful human control over swarms of robots [9].

A large number of works on HSI have been published since Kolling *et al.* [10] presented the first survey of the topic. The aim of this paper is to review these works to gain an understanding of where state-of-the-art HSI research is at, and to identify gaps in knowledge that still must be filled to enable swarms of robots to operate in the real world with the aid of a human operator. Current surveys on HSI are largely outdated as the field is progressing rapidly. As a result, there is a need for a new updated survey paper on the topic.

HSI will be defined in the next section. In Section 3, state-of-the-art methods that can be used for remote and proximal interaction between swarms of robots and a human operator are reviewed. Four methods for transmitting an operator's intent to a swarm are presented in Section 4, while levels of autonomy and flexible autonomy in HSI are covered in Section 5. A discussion of the gaps in knowledge that still must be filled to enable swarms of robots to operate in the real world is presented in the following section. Section 7 summarizes and concludes the paper.

2. HUMAN SWARM INTERACTION

In HSI, one human traditionally interacts or collaborates with swarms of robots that coordinate among themselves to achieve a mission objective [11]. State-of-the-art techniques have enabled a single human to supervise a heterogeneous swarm of 174 ground and air vehicles [12].

Unlike single-robot operations, where operators typically control the platform's movement manually, HSI involves humans performing higher-level mission management tasks. According to Steane *et al.* [2], HSI operators may have to transition between being on-the-loop (where the human is involved in a supervisory role) and in-the-loop (where the human is actively involved in the low-level decision-making process). This capability is important when considering that human operators can be viewed as a failsafe to guarantee that the swarm's behavior aligns with its mission objectives.

Swarms of robots are commonly regarded as fully autonomous, self-organized, and without central control [13]. However, fully autonomous swarms operating in unstructured dynamic environments are not expected to be a reality soon due to their lack of human-like general intelligence [10]. As technology becomes more sophisticated and robot swarms demonstrate an increased ability to perform autonomously, HSIs will still be required, but at a higher level. The ideal role of a human is, in fact, at the supervisor or teammate level rather than at a level where the human operator manually controls the individual robots in the swarm [4], [14], [15].

3. INTERACTING WITH SWARMS OF ROBOTS

Based on the reviewed literature, a significant challenge in interacting with remote swarms is communication. Specifically, the latency of communication channels between the human operator and the swarm presents a significant issue. Increased latency causes delays in bidirectional interactions, making it hard for the operator to accurately comprehend the current state of the swarm [6], [16]. This is a major problem for HSIs in defense contexts, as radio frequency channels often are jammed by an adversary. Remote interaction with swarms of robots will be discussed in greater detail in the following sub-section.

3.1. Remote interaction

Since robot swarms will often enter hazardous or inaccessible environments, remote interaction is expected to be the standard approach. HSI solutions designed for this purpose should allow humans to interact with robot swarms regardless of the geographical distance between them [17].

In HSI scenarios where the number of robots surpasses that of human operators, efficient interaction becomes challenging because of issues related to workload, perception, and situational awareness. Consequently, there is a need for intelligent interface designs to address these challenges. Traditional remote interaction interfaces predominantly utilize screen-based solutions due to their ease of implementation. However, recent advancements have seen a rise in the adoption of immersive interfaces employing virtual reality (VR) or augmented reality (AR). These advanced solutions have demonstrated efficacy in reducing operator workload and enhancing situational awareness [11].

Adams *et al.* [18] presented a VR-based solution that was used in DARPA's offensive swarm-enabled tactics program, investigating whether a single human can supervise a heterogeneous swarm of unmanned ground vehicles (UGVs) and unmanned aerial vehicles (UAVs) that are completing tasks in real-world environments. An immersive interaction interface (I3) was used to interact with the swarm. I3 is a VR interface developed using the Unity game engine. It utilizes SteamVR and the Valve Index hardware system. The interface enables a swarm commander to interact with swarms from a dedicated command center near a battlefield. Experiment results demonstrate that the interface enables a single human to deploy a swarm of 100 heterogeneous robots to conduct missions in urban environments. The interface is described in detail in [19].

Jang *et al*. [20] presented a VR-based solution for beyond-line-of-sight HIS, making make use of Leap Motion, a head-mounted display, and an avatar that can supervise a swarm of robots via robot-oriented, swarm-oriented, and environment-oriented interactions. In robot-oriented interaction, the human gives direct commands to individual robots, while in swarm-oriented interactions, a human operates a leader robot. In environment-oriented interactions, the human modifies the environment that robots interact with by creating virtual obstacles or walls. Experiments using three real and six virtual robots indicate that the system proposed by the authors is suitable for swarm robotics in large, remote environments. However, the system should be regarded as being closer to a multi-robot system rather than a true swarm, as all robots are connected to a centralized control center. To turn the proposed solution into a true swarm, each robot should be equipped with individual decision-making capabilities so that desired collective behaviors can be achieved even if only a subset of the robots are connected to the centralized hub.

In another attempt to devise a solution for remote interaction with a swarm, Macchini *et al.* [21] proposed a Leap Motion-based interface for controlling a swarm of four simulated UAVs through a teleoperation task. In their solution, a leader drone is controlled by a human operator, while the remaining agents are controlled by the Reynolds' algorithm. The swarm is visualized in third-person view using a head-mounted VR display, and the swarm can perform eight different maneuvers, namely front-back motion, up-down motion, right-left motion, and expansion-contraction. Results showed that 10 human subjects were all able to navigate a swarm of simulated UAVs through a path using the proposed interface. However, it would be desirable to test the solution on a physical drone swarm to investigate if the results are transferable to the real world.

Sachidanandam *et al*. [17] presented an example of an AR solution that has been developed for remote access HIS, developing an interface that allows users to perceive and operate a group of robots remotely through a video call, and ran user studies where participants performed a navigation task where a robot swarm was directed through sequences of goals in cluttered environments. The participants executed these tasks using an unaugmented version of the interface that only displays the robots and the environment, and with an augmented version that offered more information, including the robot swarm boundary, current heading, shortest path to a goal, and indications of collision safety barrier violations. Findings show that there is statistically significant improvement in collision safety barrier violations and tracking accuracy when the human participants used the augmented user interface. Through surveys, it was furthermore shown that human operators overwhelmingly prefer the augmented interface. These results show that AR-based solutions can improve interaction with remote HSI.

Another solution for remote interaction with swarms of robots is presented by Williamson *et al*. [22] [22]. A 2D sketch-based interface that can be used either with a mouse or a stylus was presented. The interface displays information collected by robots on a map. For commands, the operator can draw gestures and provide additional parameters via further gestures or keyboard input. An AR interface application deployed to HoloLens 2 was also created. The interface uses hand tracking technology to recreate features available in the 2D sketch interface and provides a 3D interface to the operator. It presented map information in multiple formats—top-down, 3D, and ground-level views. The AR interface supports voice commands, enabling multimodal robot control. Field tests used the sketch interface primarily for swarm command and the AR interface for enhanced situational awareness during operations. Both interfaces worked together: the sketch interface provided route information, while the AR interface designated no-go zones. The design enabled efficient management of a large-scale swarm network consisting of UAVs and UGVs in the field, and clear information delivery without distracting users.

In [23], a technique for remote interaction with swarms of robots using eye movements is presented. The work focuses on coverage control using Voronoi partitioning. The work is implemented using HoloLens 2 and TurtleBot robots for practical experiments. Experimental results show that the method maintained high performance in challenging environments, achieving over 85% coverage efficiency.

3.2. Proximal interaction

Proximal interactions enable an operator to directly observe the swarm and engage with it within a shared environment. In scenarios where the swarm can sense the presence of the human operator, the operator can, in certain cases, act as a special member of the swarm—using local interactions to influence its behaviour. This approach opens the possibility for multiple human operators to collaboratively control and influence the swarm in a distributed manner [10].

A human operator interacts with a proximal robot swarm consisting of up to 20 wheeled tabletop Zooids robots using gestures, touch, and verbal instructions [24]. Findings indicate that user-elicited interaction methods are closely linked to both the number of robots involved and their relative proximity. It was also revealed that the effective operation of robot swarms will require dynamic, state-dependent interaction vocabularies, as future swarms are expected to be increasingly mobile and adaptive.

A multi-modal interface that makes use of a combination of haptic and verbal input to operate two AR Drone 2 UAVs is presented by Pourmehr *et al*. [25]. A user can identify individual or groups of robots using haptic stimuli (e.g., by touching the robots). The user can also name robots using a voice command. Subsequent commands such as "take off" and "land" can be addressed to the named robots. They demonstrated that their solution allows a single human to operate a multi-robot system in semi-realistic coordinated exploration missions. However, experiments on larger numbers of UAVs will be required to demonstrate that this solution will enable a human operator to control swarms of robots.

In the solution presented by Gromov *et al*. [26], a human operator can communicate with one or more robots using gestures and speech with the aid of a set of off-the-shelf wearable devices when the human and the robots share the same physical environment. A relative localization system to transform gesture-related information into a common reference frame for the human and robots had been developed. No global positioning system is therefore required. Vocal messages and light emitting diodes are used to offer feedback from the robots to the operator. The solution has been tested with three Pioneer P3AT and four Foot-bot wheeled robotic platforms. The solution allows the human to command robots to go to a point in space, move in a particular direction, search for survivors for 20 minutes, and so on.

Swarm Touch presents an alternative interaction method for HSI where an operator controls the formation of Crazyflie 2.0 quadrotors. The operator receives vibrotactile feedback through a glove equipped with five vibrotactile actuators attached to their fingertips. This method considers the operator's hand velocity and adjusts the formation shape and dynamics of the swarm accordingly. A user study involving six participants indicated that tactile feedback enhances the operator's ability to guide drone formations and increases HSI interactivity [27].

Another interface for proximal interaction with groups of robots is presented by Fedoseev *et al*. [28]. They proposed Dandelion Touch, a haptic display that delivers feedback to a user's fingertips from a swarm of Crazyflie drones through flexible cords. Technology enables a user to control the swarm with four gestures: moving right, left, forward, and backward. They use an Oculus Quest headset for hand tracking and interaction with obstacles in a virtual environment. Artificial potential fields are used to avoid internal collisions between Crazyflie and with the user's hand.

Serpiva *et al*. [29] presented a novel HSI technology that allows users to directly operate a swarm of Crazyflie 2.0 UAVs through trajectory drawing using a hand gesture interface. The hand gesture interface consists of a single webcam along with hand tracking and gesture recognition modules. A deep neural network is used in the gesture recognition module to obtain high-precision gesture classification. The interface enables the user to change the swarm's shape and formation through free-form trajectory generation control and trajectory drawing. Potential fields are used to achieve path planning and collision avoidance between the UAVs. The technology was tested on seven human participants. Results from these tests show that the proposed technology achieves both high variety and high accuracy swarm control.

Canal *et al*. [30] presented a brain-computer interface for non-invasive electroencephalogram-based control of a high complexity ground moving robot swarm. The solution enables an operator to issue high-level formation control commands that are performed by the swarm in a distributed manner. The feasibility of the proposed solution was demonstrated through large-scale user testing on virtual and real robot swarms.

Chaudhary *et al*. [31] presented a HSI method that uses camera-based full-body action recognition to operate a flock of UAVs. They determined the full-body pose of a human operator and made use of a k-nearest neighbor technique to classify the movement made by the human. The swarm makes use of a leader-follower approach and the identified movement to decide what direction to move in. The presented method was tested on three simulated UAVs in the Gazebo simulator and on a real-world UAV equipped with a camera in an outdoor setting. Experiment results demonstrate that their proposed method enables direct operation of UAV swarms when the human shares workspace with the swarm.

In [32], a human–swarm interface that integrates both robot-oriented and environment-oriented interaction modalities for a collective transport scenario is presented. Robot-oriented modality allows a human operator to select and interact with individual robots, while the environment-oriented modality enables the operator to modify the environment to indicate that the swarm should perform a specific task, such as moving an object to a designated location. The interface was implemented as an AR application for iOS 9+ handheld devices, chosen for its intuitive touch-based graphical interface and cost-effectiveness. The authors conducted user studies with 10 participants, each operating four or five ground robots, to evaluate the system's usability and effectiveness. Results demonstrated that combining robot-oriented and environment-oriented commands enhances performance in collective transport tasks, as it reduces the number of commands required to accomplish a given goal.

4. CONTROL METHODS

Methods that can be used to control a swarm are separated into four classes: i) selecting swarm behaviors and algorithms, ii) altering the parameters of the swarm's control algorithms, iii) indirect control by altering the environment, and vi) control through swarm leadership strategies [33]. Each of these control methods will be discussed below.

4.1. Behavior and algorithm selection

Behavior and algorithm selection-based control assumes that an operator can provide inputs at specific times by selecting preset combinations of behaviors (e.g., plays), individual behaviors, or particular swarm algorithms. It also presupposes that the operator has access to libraries of algorithms capable of executing various swarm behaviors [10].

Controlling a swarm through behavior or algorithm selection appears to be an effective approach when the robots are highly autonomous and capable of operating reliably without continuous human supervision. Once the swarm is instructed to execute a specific behavior, a combination of behaviors, or an algorithm, the operator depends on both the autonomy of individual robots and the collective autonomy of the swarm to manage local coordination, inter-robot communication, and obstacle avoidance. This type of control, according to Kolling *et al.* [10], does not pose considerable constraints on the communications network. Behavior selection-based control was used in [34]–[36].

4.2. Control via parameter setting

Most swarm algorithms rely on sets of parameters for their operations. Human operators can control these parameters, which is the most indirect form of guiding a swarm and depends significantly on the type of autonomous behavior and swarm hardware [37]. One challenge with swarms is that the control parameters do not directly determine their behavior; instead, they influence it indirectly through the interactions among individual robots and between the swarm and its environment [10]. Works that consider control via parameter setting can be found in [38], [39].

4.3. Environmental influence

Swarm robots can also be controlled by modifying parts of the environment. This method has been implemented using virtual beacons and virtual pheromones [10]. Under this approach, the swarm continues to function according to the same rules as when it was deployed. If a specific behavior is guaranteed to emerge, this form of control does not necessarily affect that guarantee.

Oliveira *et al.* [40] used virtual beacons, which were sources of attractive and repulsive potential fields, to enable humans to control a flocking swarm through two maze-like structures in simulation. Through user studies on 20 human subjects, the authors found that their virtual beacons are easy to implement and relatively simple to learn to use. An example of the use of virtual pheromones to control a swarm is given by Walter *et al.* [41]. Therein, it was demonstrated that operators can control up to 50 000 virtual UAVs in simulation using virtual pheromones.

4.4. Leader selection

One can furthermore deal with the complexity of controlling a swarm by enabling operators to control a subset of the swarm. According to Aldhaheri *et al.* [42], controlling a few swarm members allows for significant human intervention and is a reliable HSI mechanism. These controlled swarm members are often regarded as leaders, as they influence the rest of the swarm. The use of leaders facilitates more engaging forms of control, such as teleoperation. However, this control method can be vulnerable to adversarial attacks targeting the swarm leaders and places relatively high demands on the operator due to the increased workload associated with teleoperation.

In [31], a leader–follower approach to HSI was implemented, in which one UAV is designated as the leader and serves as the recipient of commands from the human operator. The remaining members of the flock respond to the leader's movements, gradually adjusting their positions and drifting in the same direction as the leader robot.

In [43], a leader quadrotor that interacts directly with a human operator guides a group of follower quadrotors to track a human-defined trajectory in a desired formation pattern. The swarm is designed to temporarily and autonomously adjust its motion trajectories if a human command leads to an unsafe situation, such as encountering obstacles along the path. Experiments conducted with six physical Crazyflie quadrotors confirmed that the proposed approach successfully achieves formation tracking, even in the presence of dynamic obstacles.

A formation control method for contactless gesture-based HSI between multi-rotor UAV teams and human workers is presented by Krátký *et al.* [44]. The system monitors worker safety, especially at heights, using one UAV as a sensor-equipped formation leader to detect humans and recognize gestures. Follower UAVs maintain a set formation around the worker, offering multiple viewpoints. Workers use hand gestures to direct UAV movements and mission tasks without extra communication channels or markers. Tests with three UAVs and a human worker in simulated scenarios and in field experiments show the approach is effective and responsive.

5. AUTONOMY IN HUMAN-SWARM INTERACTION

Four levels of autonomy for swarms were defined in [45], namely: i) full autonomy, ii) machine-oriented semi-autonomy, iii) human-oriented semi-autonomy, and iv) manual operation. A fully autonomous swarm performs tasks without intervention from the human [15]. In machine-oriented semi-autonomy, the swarm mostly performs autonomously and simply informs the human operator of important events, while in human-oriented semi-autonomy, the swarm frequently relies on human instructions. In manual operation, the human operator makes all the decisions and performs the actions of the swarm [15].

The human operator's workload is influenced by the swarm's level of autonomy. At lower levels of autonomy, the operator is responsible for planning and executing low-level actions, which leads to a substantial workload. As the level of autonomy increases, the operator's role becomes more supervisory, focusing on making mission-level decisions and monitoring overall system performance.

Fixing the level of autonomy can produce a rigid system that does not adapt to real-time changes [16]. In real-world operations, a human operator will therefore not solely interact with the swarm at a single system level, but will continuously alter the level of automation as the mission develops [46]. If the level of autonomy is low, then the human can be overloaded, whereas if the level of autonomy is high, the human can become underloaded. Neither of these situations is ideal and may lead to difficulties in sustaining situational awareness. It can also lead to complacency and a drop in performance. This is consistent with findings that suggest that both too much and too little human influence can result in performance degradation of the swarm [6]. It is therefore important that the workload is held within acceptable ranges [4], [47].

This brings us flexible autonomy. According to Chen and Barnes [48], flexible autonomy can be classified as adaptable, adaptive, and mixed-initiative. This is based on whether the decision to adapt is taken by the human, the software, or both. In adaptable systems, the human invokes the appropriate level of autonomy. Adaptable autonomy has been critiqued for increasing the workload associated with autonomy decisions to the human operator [15]. In adaptive systems, the decision is taken by the software. The load on the human operator is therefore waived. The main drawback with this solution is that authority is in the hands of robots rather than the human. The final category of flexible autonomy is mixed-initiative systems, in which both human and software share responsibility for making adaptation decisions. These systems combine elements of adaptable and adaptive autonomy, allowing the human operator to intervene in or override decisions made by the software. Designs of mixed initiative solutions are presented in [15], [16].

6. DISCUSSION

Many approaches to HSI have been formulated to date. However, HSI is far from being a solved problem, and effective interfaces that can be used to interact with robot swarms are at their early stages. More work on intuitive methods for controlling swarms of unspecified sizes, while at the same time accounting for the human operator's cognitive load, must therefore be developed. It is also noted that most of the techniques found in literature focus on proximal interactions, while the default mode of operation of swarms is likely to be beyond-line-of-sight interaction, as swarms of robots will often enter otherwise dangerous or inaccessible environments. It is therefore suggested that more research into techniques for remote interaction with robotic swarms is conducted. This includes research into methods that enable remote interaction with swarms of swarms where an operator must manage very large numbers of platforms.

There is furthermore a lack of consistency in HSI interfaces, as all the reviewed work has developed its own solutions. It would be beneficial if the community could develop a common open-source interface so that multiple parties can work on it. This would lead to greater momentum, greater support, and adoption.

More work on HSI in degraded communications environments is also required, potentially aided by delay-tolerant networking, which enables the swarm to act as a self-organizing ad-hoc network that ferries data between the swarm and a human operator [8]. Preliminary work in this direction is presented in [49]. However, a delay-tolerant HSI interface is still lacking.

Additional research into swarm autonomy is also required to facilitate efficient supervisory control. One prospective avenue in this regard is to conduct research into hyper-heuristic selection mechanisms so that swarms can select algorithms or behaviors to execute autonomously. Another avenue of research is to enable play-based control so that swarms execute combinations of behaviors autonomously. This will enable human operators to work on a higher supervisory level but will require that the swarms have access to libraries of appropriate behaviors or control algorithms. Preliminary work on autonomous selection of swarm algorithms has been presented in [50].

Most HSI solutions are furthermore tested in simulation or with a small number of robots. There is a scarcity of solutions that are validated in the real world, particularly in large-scale swarm deployments. It is recommended that more efforts be invested in addressing this issue.

Lastly, there is room for more work on trust in HSI, as robotic swarms can only be used by humans if they can be trusted. Trust can be increased by making the decision-making process of the swarm more transparent to the human user. One can also use confidence scores, which indicate the likelihood that the swarm is correct, or one can use uncertainty communication, which highlights when the swarm is unsure of a prediction. The latter approach helps users identify errors in the swarm's reasoning and recognize when the swarm is uncertain so that users can adjust their trust accordingly. Preliminary work that investigates trust in HSI is presented in [51]–[54].

7. CONCLUSION

This paper reviewed recent activities in HSI research. The paper commenced with a short description of swarming in general. It then discussed HSI and explained how a human operator can benefit swarm missions. Novel methods for remote and proximal interaction with robotic swarms were then reviewed. Four control methods that can be used to transmit an operator's intent to a swarm were also presented. Behavior and algorithm selection-based control, control via parameter setting, control via environmental influence, and control via leaders were covered. Levels of autonomy and flexible autonomy in HSI were furthermore described in detail. At the end of the paper, a discussion of the gaps in knowledge that still must be filled to enable swarms of robots to operate in the real world was presented. It was found that most of the techniques described in literature focus on proximal interactions, while the default mode of operation of swarms is likely to be beyond-line-of-sight interaction, as swarms of robots will often enter otherwise dangerous or inaccessible environments. It was therefore suggested that more research into techniques for remote interaction with robotic swarms be conducted. This includes research into methods that enable remote interaction with swarms of swarms where an operator must manage very large numbers of platforms. More work on HSI in degraded communications environments is also required. In particular, for defense applications, adversaries are likely to jam communications channels. Additional research into swarm autonomy is furthermore needed to facilitate efficient supervisory control. There is also room for more work on trust in HSI, as robotic swarms can only be used by humans if they can be trusted.

ACKNOWLEDGMENTS

The author thanks Dr Simon Crase for reviewing the paper and providing insightful comments.

FUNDING INFORMATION

Author state no funding is involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Jan Carlo Barca	✓	✓		✓	✓	✓		✓	✓	✓			✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Derived data supporting the findings of this study are available from the corresponding author JCB on request.

REFERENCES

[1] M. Brambilla, E. Ferrante, M. Birattari, and M. Dorigo, "Swarm robotics: a review from the swarm engineering perspective," *Swarm Intelligence*, vol. 7, no. 1, pp. 1–41, Mar. 2013, doi: 10.1007/s11721-012-0075-2.

[2] V. Steane, J. Oakes, S. Palmer, and M. Chattington, "Human-swarm partnerships: a systematic review of human factors literature," *AHFE International*, 2023, doi: 10.54941/ahfe1003754.

[3] J. C. Barca and Y. A. Sekercioglu, "Swarm robotics reviewed," *Robotica*, vol. 31, no. 3, pp. 345–359, May 2013, doi: 10.1017/S026357471200032X.

[4] A. Hussein, "Performance, trust, and transparency for effective human-swarm interaction," UNSW Sydney, 2021.

[5] C. Nam, P. Walker, H. Li, M. Lewis, and K. Sycara, "Models of trust in human control of swarms with varied levels of autonomy," *IEEE Transactions on Human-Machine Systems*, vol. 50, no. 3, pp. 194–204, Jun. 2020, doi: 10.1109/THMS.2019.2896845.

[6] C. C. Ashcraft, M. A. Goodrich, and J. W. Crandall, "Moderating operator influence in human-swarm systems," in *2019 IEEE International Conference on Systems, Man and Cybernetics (SMC)*, 2019, pp. 4275–4282.

[7] P. Zhu, Z. Zeng, W. Yao, W. Dai, H. Lu, and Z. Zhou, "DVRP-MHSI: dynamic visualization research platform for multimodal human-swarm interaction," *IEEE Robotics and Automation Letters*, vol. 10, no. 6, pp. 5665–5672, Jun. 2025, doi: 10.1109/LRA.2025.3560825.

[8] J. D. Rockbach, I. Schlangen, and M. Bennewitz, "Self-organising distributed sensor fusion networks for hierarchical swarm control and supervision," in *2023 IEEE Symposium Sensor Data Fusion and International Conference on Multisensor Fusion and Integration (SDF-MFI)*, 2023, pp. 1–6.

[9] J. D. Rockbach, "Enhancing human self-regulation with controllable robot swarms acting as extended bodies," in *2023 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, 2023, pp. 4104–4109.

[10] A. Kolling, P. Walker, N. Chakraborty, K. Sycara, and M. Lewis, "Human interaction with robot swarms: a survey," *IEEE Transactions on Human-Machine Systems*, vol. 46, no. 1, pp. 9–26, Feb. 2016, doi: 10.1109/THMS.2015.2480801.

[11] A. Dahiya, A. M. Aroyo, K. Dautenhahn, and S. L. Smith, "A survey of multi-agent human–robot interaction systems," *Robotics and Autonomous Systems*, vol. 161, p. 104335, Mar. 2023, doi: 10.1016/j.robot.2022.104335.

[12] E. M. Taranta, A. Seiwert, A. Goeckner, K. Nguyen, and E. Cherry, "From warfighting needs to robot actuation: a complete rapid integration swarming solution," *Field Robotics*, vol. 3, pp. 460–515, Mar. 2023, doi: 10.55417/fr.2023015.

[13] J. Kaduk, M. Cavdan, K. Drewing, A. Vatakis, and H. Hamann, "Effects of human-swarm interaction on subjective time perception," in *Proceedings of the 2023 ACM/IEEE International Conference on Human-Robot Interaction*, Mar. 2023, pp. 456–465, doi: 10.1145/3568162.3578626.

[14] C. Xu and H. Song, "Mixed initiative balance of human-swarm teaming in surveillance via reinforcement learning," in *2021 IEEE/AIAA 40th Digital Avionics Systems Conference (DASC)*, 2021, pp. 1–10.

[15] A. Hussein and H. Abbass, "Mixed initiative systems for human-swarm interaction: opportunities and challenges," in *2018 2nd Annual Systems Modelling Conference (SMC)*, 2018, pp. 1–8.

[16] A. Hussein *et al.*, "Towards bi-directional communication in human-swarm teaming: a survey," arXiv: *1803.03093*, Mar. 2018.

[17] S. O. Sachidanandam, S. Honarvar, and Y. Diaz-Mercado, "Effectiveness of augmented reality for human swarm interactions," in *2022 International Conference on Robotics and Automation (ICRA)*, 2022, pp. 11258–11264.

[18] J. A. Adams, J. Hamell, and P. Walker, "Can a single human supervise a swarm of 100 heterogeneous robots?," *IEEE Transactions on Field Robotics*, vol. 2, pp. 46–80, 2025, doi: 10.1109/TFR.2024.3502316.

[19] P. Walker, J. Hamell, C. A. Miller, J. Ladwig, H. Wauck, and P. K. Keller, "Immersive interaction interface (I3): a virtual reality swarm control interface," *IEEE Transactions on Field Robotics*, vol. 1, pp. 424–445, 2024, doi: 10.1109/TFR.2024.3499913.

[20] I. Jang, J. Hu, F. Arvin, J. Carrasco, and B. Lennox, "Omnipotent virtual giant for remote human--swarm interaction," in *2021 30th IEEE International Conference on Robot \& Human Interactive Communication (RO-MAN)*, 2021, pp. 488–494.

[21] M. Macchini, L. De Matteis, F. Schiano, and D. Floreano, "Personalized human-swarm interaction through hand motion," *IEEE Robotics and Automation Letters*, vol. 6, no. 4, pp. 8341–8348, Oct. 2021, doi: 10.1109/LRA.2021.3102324.

[22] B. M. Williamson, E. M. Taranta, Y. M. Moolenaar, and J. J. LaViola, "Command and control of a large-scale swarm using natural human interfaces," *Field Robotics*, vol. 3, pp. 301–322, Feb. 2023, doi: 10.55417/fr.2023009.

[23] Z. Fang, J. Qin, J. Qin, Q. Ma, R. Han, and Q. Liu, "Eye movement-based human–swarm interaction for coverage control of mobile robots with constraints," *IEEE Transactions on Industrial Electronics*, vol. 72, no. 6, pp. 6454–6464, Jun. 2025, doi: 10.1109/TIE.2024.3497343.

[24] L. H. Kim, D. S. Drew, V. Domova, and S. Follmer, "User-defined swarm robot control," in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, Apr. 2020, pp. 1–13, doi: 10.1145/3313831.3376814.

[25] S. Pourmehr *et al.*, "'You are green': a touch-to-name interaction in an integrated multi-modal multi-robot HRI system," in *Proceedings of the 2014 ACM/IEEE international conference on Human-robot interaction*, Mar. 2014, pp. 266–267, doi: 10.1145/2559636.2559806.

[26] B. Gromov, L. M. Gambardella, and G. A. Di Caro, "Wearable multi-modal interface for human multi-robot interaction," in *2016 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*, 2016, pp. 240–245.

[27] E. Tsykunov, L. Labazanova, A. Tleugazy, and D. Tsetserukou, "SwarmTouch: tactile interaction of human with impedance controlled swarm of nano-quadrotors," in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2018, pp. 4204–4209.

[28] A. Fedoseev, A. Baza, A. Gupta, E. Dorzhieva, R. N. Gujarathi, and D. Tsetserukou, "Dandeliontouch: high fidelity haptic rendering of soft objects in VR by a swarm of drones," in *2022 IEEE international Conference on Systems, Man, and Cybernetics (SMC)*, 2022, pp. 1078–1083.

[29] V. Serpiva, E. Karmanova, A. Fedoseev, S. Perminov, and D. Tsetserukou, "DronePaint: swarm light painting with DNN-based gesture recognition," in *Special Interest Group on Computer Graphics and Interactive Techniques Conference Emerging Technologies*, Aug. 2021, pp. 1–4, doi: 10.1145/3450550.3465349.

[30] G. Canal, Y. Diaz-Mercado, M. Egerstedt, and C. Rozell, "A low-complexity brain–computer interface for high-complexity robot swarm control," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 31, pp. 1816–1825, 2023,

doi: 10.1109/TNSRE.2023.3257261.

[31] A. Chaudhary, T. Nascimento, and M. Saska, “Controlling a swarm of unmanned aerial vehicles using full-body k-nearest neighbor based action classifier,” in *2022 International Conference on Unmanned Aircraft Systems (ICUAS)*, 2022, pp. 544–551.

[32] J. Patel, Y. Xu, and C. Pinciroli, “Mixed-granularity human-swarm interaction,” in *2019 International Conference on Robotics and Automation (ICRA)*, 2019, pp. 1059–1065.

[33] R. da Silva Tchilian, U. F. Moreno, and M. Netto, “Human–swarm interaction simulation platform to assess sense of agency,” *Journal of Control, Automation and Electrical Systems*, vol. 35, no. 2, pp. 235–251, Apr. 2024, doi: 10.1007/s40313-023-01058-6.

[34] P. Walker, S. Nunnally, M. Lewis, N. Chakraborty, and K. Sycara, “Levels of automation for human influence of robot swarms,” *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 57, no. 1, pp. 429–433, Sep. 2013, doi: 10.1177/1541931213571093.

[35] N. E. Leonard, D. A. Paley, R. E. Davis, D. M. Fratantoni, F. Lekien, and F. Zhang, “Coordinated control of an underwater glider fleet in an adaptive ocean sampling field experiment in Monterey Bay,” *Journal of Field Robotics*, vol. 27, no. 6, pp. 718–740, Nov. 2010, doi: 10.1002/rob.20366.

[36] H. Li, J. Bang, S. Nagavalli, C. Nam, M. Lewis, and K. Sycara, “Human interaction through an optimal sequencer to control robotic swarms,” in *2018 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, 2018, pp. 3807–3812.

[37] A. Kolling, K. Sycara, S. Nunnally, and M. Lewis, “Human-swarm interaction: an experimental study of two types of interaction with foraging swarms,” *Journal of Human-Robot Interaction*, vol. 2, no. 2, Jun. 2013, doi: 10.5898/JHRI.2.2.Kolling.

[38] Z. Kira and M. A. Potter, “Exerting human control over decentralized robot swarms,” in *2009 4th International Conference on Autonomous Robots and Agents*, 2009, pp. 566–571.

[39] M. Catellani, E. Mazzocco, F. Bertoncelli, and L. Sabattini, “Distributed control for human-swarm interaction in non-convex environments using Gaussian mixture models,” *IFAC-PapersOnLine*, vol. 56, no. 2, pp. 3314–3319, 2023, doi: 10.1016/j.ifacol.2023.10.1475.

[40] T. L. Oliveira, M. R. Batista, and R. A. F. Romero, “Analysis of human-swarm interaction through potential field manipulation,” in *2017 Latin American Robotics Symposium (LARS) and 2017 Brazilian Symposium on Robotics (SBR)*, 2017, pp. 1–6.

[41] B. Walter, A. Sannier, D. Reiners, and J. Oliver, “UAV swarm control: calculating digital pheromone fields with the GPU,” *The Journal of Defense Modeling and Simulation: Applications, Methodology, Technology*, vol. 3, no. 3, pp. 167–176, Jul. 2006, doi: 10.1177/154851290600300304.

[42] S. Aldhaheri, F. Renda, and G. De Masi, “Underwater human-robot and human-swarm interaction: a review and perspective,” *OCEANS 2024-Singapore*, pp. 1–9, 2024.

[43] M. Li, J. Qin, J. Li, Q. Liu, Y. Shi, and Y. Kang, “Game-based approximate optimal motion planning for safe human-swarm interaction,” *IEEE Transactions on Cybernetics*, vol. 54, no. 10, pp. 5649–5660, Oct. 2024, doi: 10.1109/TCYB.2023.3340659.

[44] V. Krátký *et al.*, “Gesture-controlled aerial robot formation for human-swarm interaction in safety monitoring applications,” *IEEE Robotics and Automation Letters*, vol. 10, no. 8, pp. 8244–8251, Aug. 2025, doi: 10.1109/LRA.2025.3583607.

[45] Z.-Q. Mi and Y. Yang, “Human-robot interaction in UVs swarming: a survey,” *International Journal of Computer Science Issues (IJCSI)*, vol. 10, no. 2 Part 1, p. 273, 2013.

[46] O. Bjurling, R. Granlund, J. Alfredson, M. Arvola, and T. Ziemke, “Drone swarms in forest firefighting: a local development case study of multi-level human-swarm interaction,” in *Proceedings of the 11th Nordic Conference on Human-Computer Interaction: Shaping Experiences, Shaping Society*, Oct. 2020, pp. 1–7, doi: 10.1145/3419249.3421239.

[47] A. O. Abioye, M. Naiseh, W. Hunt, J. Clark, S. D. Ramchurn, and M. D. Soorati, “The effect of data visualisation quality and task density on human-swarm interaction,” in *2023 32nd IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*, 2023, pp. 1494–1501.

[48] J. Y. C. Chen and M. J. Barnes, “Human–agent teaming for multirobot control: a review of human factors issues,” *IEEE Transactions on Human-Machine Systems*, vol. 44, no. 1, pp. 13–29, Feb. 2014, doi: 10.1109/THMS.2013.2293535.

[49] P. Smith, A. Aleti, V. C. S. Lee, R. Hunjet, and A. Khan, “Robotic hierarchical graph neurons: a novel implementation of HGN for swarm robotic behaviour control,” *Expert Systems with Applications*, vol. 186, p. 115675, Dec. 2021, doi: 10.1016/j.eswa.2021.115675.

[50] S. Yu, A. Song, and A. Aleti, “A study on online hyper-heuristic learning for swarm robots,” in *2019 IEEE Congress on Evolutionary Computation (CEC)*, 2019, pp. 2721–2728.

[51] A. O. Abioye *et al.*, “A user study evaluation of predictive formal modelling at runtime in human-swarm interaction,” *ACM Transactions on Human-Robot Interaction*, vol. 14, no. 4, pp. 1–24, Dec. 2025, doi: 10.1145/3727989.

[52] D. A. Williams, A. Chapman, D. R. Little, and C. Manzie, “Asymmetrical trust modeling for human-robot swarm interactions,” in *2025 20th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, 2025, pp. 1722–1726.

[53] M. Huo and H. Duan, “Artificial intelligence-enabled authority game for human--swarm control: toward adaptive levels of autonomy,” *IEEE Systems, Man, and Cybernetics Magazine*, vol. 11, no. 2, pp. 84–91, 2025.

[54] H. He, M. Huo, and H. Duan, “Distributed cooperative control for human-unmanned aerial vehicle swarm teaming in target tracking,” in *2024 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, 2024, pp. 2062–2067.

BIOGRAPHIES OF AUTHORS

Jan Carlo Barca is a senior researcher in advanced teaming and swarming at the Defence Science and Technology Group in Australia. His major research interests are in the areas of swarm robotics, swarm intelligence, and counter swarming. He has devised novel technology for swarms of UAVs, UGVs, and climbing robots. He has published work at several international conferences and in high-level journals. He has also managed projects for industry and academia. He can be contacted via email at jan_carlobarca@hotmail.com.