Opportunities and Challenges in Human-Swarm Interaction: Systematic Review and Research Implications

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***Abstract*—We conducted a Systematic Literature Review on scientific papers that examined the interaction between operators and drone swarms based on the use of a command and control center. We present the results of a meta-analysis of nine scientific papers published in the ACM DL and IEEE Xplore databases. Our findings show that research on human-drone swarm interaction shows a disproportionate interest in hand gestures compared to other input modalities for drone swarm control. Furthermore, all articles reviewed exclusively explored gestures and the size of the swarm used in the studies was limited, with a median of 3.0 and an average of 3.8 drones per study. We compiled an inventory of interaction modalities, recognition techniques, and application types from the scientific literature, which is presented in this paper. On the basis of our findings, we propose four areas for future research that can guide scientific investigations and practical developments in this field.**

Keywords*—*Human swarm interactions; input modalities; swarm control

Fig. 1. Description of concept interaction between operators and drone swarms, based on the use of a command and control center.

I. Introduction

Interacting with drone swarms is becoming fascinating for many people, but is still futuristic for many fields of scientific study [1]. However, the human-drone swarm interaction is made possible by the large amount of work done by researchers and practitioners in this field. The scientific community has investigated and proposed new technologies [2], artifacts [3], and interaction techniques [4] to make human-drone interaction possible and allow operators to accept drone interaction and rides in public spaces [5]. This work has revealed numerous benefits to society, such as finding survivors in emergency situations [6], [7], [8], [9] or escorting lone drones moving at night [10]. Other scientific papers have focused on the guidance of drones by people crossing roads [11] or providing personal assistance [12]. These proposals with drones used on a large scale have also come with many applications and fields of use. Despite the potential drone swarms they create, a quantitative analysis of how research has developed is lacking. We find drones in a multitude of fields, from professional environments [13], leisure [14], or semi- or fully autonomous modules [15]. However, we identify drones that are used singularly [16] or are part of a swarm [17]. This exemplification highlights the diversification of domains with drones, and we, therefore, propose a high-level perspective of current and future use cases for drone swarm interaction. See Fig. 1.

First, this article describes the selection process, which represents a domain analysis of N=59 scientific articles on the interaction between operators and drone swarms based on the use of a command and control center. Second, our results have led to several future research directions. Finally, we conclude with fundamental observations and research opportunities for the field.

To the best of our knowledge, this is the first paper to analyze a scientific paper in this form; therefore, we propose the following.

1) We report results from the Systematic Literature Review conducted on the interaction between operators and drone swarms based on the use of a command and control center.
2) We draw implications for future research on the interaction between operators and drone swarms based on the use of a command and control center.
3) We propose four research directions for the scientific community to structure future scientific (*A. Input modalities and interaction technique, B. User studies and evaluations, C. Involvement of Multiple Drones in Simulations, D. Control and Command Devices and Prototypes*) investigations and practical developments in this area.

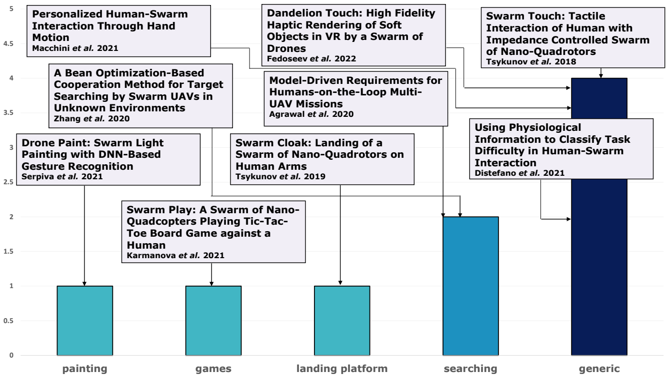

Fig. 2. Type of application interaction between operators and drone swarms, based on the use of a command and control center.

II. Study Design and Scoping Review

Previously published research in the field of human-drone swarm interaction has, for example, presented various activities in which drones are used for monitoring and assessing earthquake damage [18], investigating maritime spill [19], and delivering defibrillators [20]. All these applications involve human operators who will interact with drones through an interface, directly or indirectly, to capture images or plan drone routes. Previous research has described other forms of interaction [21], including voice and haptic interfaces [22], [23], but these have not been identified for interactions with drone swarms for emergency response.

Therefore, we present the method underlying the formation of our study during the systematic literature review of the literature to address the two research questions in the II-B section that are focused on our area of investigation for the interaction between operators and drone swarms, based on the use of a command and control center.

The substantial growth in drones in recent years[1] does not lead to a clear direction in which application domains these drone swarms are needed and what interactive modalities are required with them.

That is why we aim to map the systems and applications that have been described, studied, or envisioned in the scientific literature and that are based on the interaction between operators and drone swarms based on the use of a command and control center. There are a few scientific studies that have analyzed in detail, challenges, application domains, and detailed descriptions of previous works, all of which have focused on human-drone interaction [24], [25].

These surveys offer useful information to the community of researchers and practitioners. However, they do not provide a systematic exploration of previous work that looked at the interaction between operators and drone swarms based on the use of a command and control center in terms of the systems and applications that have been used. Here, we take a broader angle and propose a systematic literature review of the scientific literature that addresses the interaction between operators and drone swarms, based on the use of a command and control center, classifying the purposes of the applications, the domains, how data were collected, and also the systems that were used to interact with drone swarms.

A. Chosen Methodology and Steps

We conducted a systematic literature review, using the methodology proposed by Siddaway *et al.* [26] and Liberati *et al.* [27], to perform a critical analysis of the current state-of-the-art in terms of the interaction between operators and drone swarms based on the use of a command and control center. Implementing this approach was based on the identification of references of interest for our study, and therefore we identified, using queries with a specific footnote query in the ACM Digital Library[2] and IEEE Xplore[3] databases, where we identified and analyzed a body of N=59 scientific articles.

Our motivation for conducting this survey of systems and applications that address the interaction between operators and drone swarms is to provide an overview of the systems and applications, how they interact with them, and current and future use cases studied and envisioned in the scientific literature. In the following, we explain the survey method used, our research questions formulated, and how we selected and categorized the relevant articles for our study.

We have carried out data mapping that targets applications in the interaction between operators and drone swarms, based on the use of a command and control center according to the following steps:

B. First Stage: Identifying the Research Questions for Our Study

To explore the scope of applications targeting human-drone swarm interaction based on the use of a command and control center, we formed the following questions.

RQ1: *"What are the categories of applications studied or considered in human-drone swarm interaction?"*

RQ2: *"What kind of interaction modalities has been described, studied, or designed for human-drone swarm interaction based on the use of a command and control center?"*

C. Second Stage: Identifying Relevant Articles

We based our selection on academically evaluated research articles. We therefore selected the ACM Digital Library, which contains more than 3M records, and IEEE Xplore, these being the main digital libraries in Engineering and Computer Science. To identify works that could be integrated into our study we used to query:

```
"query": {
   Abstract:
   ((interaction* AND swarm*) AND
   (drone* OR  uav*) AND
   (tool* OR platform* OR
    application* OR system*))
}
"filter": {NOT VirtualContent: true}
```

[1] https://www.nytimes.com/2020/05/23/style/drones-coronavirus.html

[2] https://dl.acm.org/

[3] https://ieeexplore.ieee.org/Xplore/home.jsp

Using asterisks (*) to avoid focusing the search on a single word. Note that we focused our search on drones, and UAVs are the most popular type of consumer drone, according to the analysis by Wojciechowska *et al.* [28]. The formed query was used for both databases.

D. Third Stage: Selecting Relevant Articles

Our analysis included reviewed articles and large-scale academic articles, such as extended abstracts (e.g., postings and demonstrations), but also articles from workshops. In our selection process, we did not include sites websites or other media, as we intend to focus on classifying the purposes of the applications, the domains, how data was collected but also the systems that were used to interact with drone swarms but also on image object recognition technologies encountered in the interaction between operators and drone swarms, based on the use of a command and control center. All the selections that we refer to will be called articles throughout this scientific article. For all articles identified using queries from ACM and IEEE Xplore, we used the following exclusion criteria.

EC1: *Mandatory article was written in English, abstract and the content article.* From our analysis, we have identified two articles that do not meet the criteria [29], [30]

EC2: *Considers interactions between humans and drone swarms.* Our analysis excluded 42.37% of the articles from the total aggregate gathered from the two queries. Among these, we identify articles such as [31], [32], [33].

EC3: *Does not show one or more types of interaction.* We have excluded all articles that show no interaction with drone swarms. Our analysis reduced cumulative work by 32.20%, excluding articles such as [34], [35], [36].

After the identification process, N=59, duplicate elimination, D=3, followed. As a result, the selection and analysis process of the articles remained, N=56, which were selected based on title and abstract. Subsequently, 56 articles were evaluated for eligibility criteria based on the full text. This process eliminated 47 articles that did not follow our research direction.

Therefore, this process resulted in nine articles, which were considered relevant to the formulation of the proposed aim, and based on these we completed the aims for interaction between operators and drone swarms, based on the use of a command and control center.

E. Fourth Stage: Charting the Data for Relevant Articles

Charting is a technique to synthesize and interpret quantitative data and involves sorting the material according to the issues and themes proposed by Hilary *et al.* [37]. The process started by establishing the scopes, methods of shape recognition, and other metrics to be presented in the scientific articles. Data extraction was carried out for each item that constitutes the body of scientific articles. Each time a new domain was identified, we recorded it in the table, so that later we could quantitatively report the results that we would present. Where applications did not specify a particular domain, we noted it as generic. In addition to application areas, algorithms, and other measurements, we also performed an analysis of the distribution of articles by year; see Fig. 3.

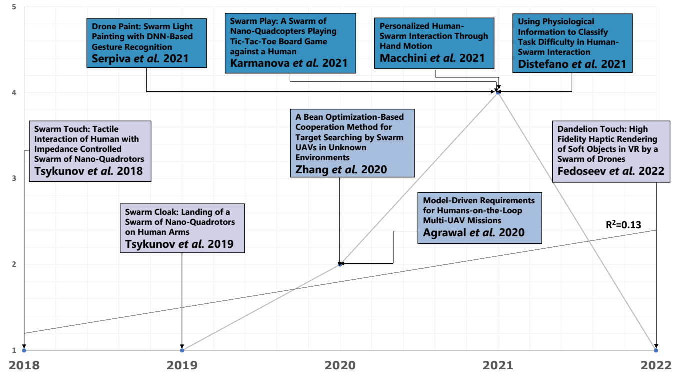

Fig. 3. Distribution by year of articles on the interaction between operators and drone swarms, based on the use of a command and control center.

III. Findings Results

The analysis was conducted using nine scientific articles [4], [38], [39], [40], [41], [42], [43], [44], [45]. This section is dedicated to selected articles on the application areas of interaction between operators and drone swarms, based on the use of a command and control center.

In terms of ❶ *application types,* painting applications account for 11% of our body of work, in which we have the "Drone Paint" application by Serpiva *et al.* [4], in which he proposes a system capable of interacting with a swarm that controls the swarm's trajectory through gestures. Another category of applications is dedicated to games, or entertainment, that occupies 11% of the total body of work, where "Swarm Play" has Karmanova *et al.* [38], which proposes the game Tic-Tac-Toe, using a swarm of drones, winning against a human user. Generic applications, which occupy the largest place in our body of work, are applications that aim to control robotic systems, such as drone swarms through navigation algorithms [40]. See Fig. 2.

The reviewed articles were published between 2018 and 2022, where the maximum ❷ *number of publications* was in 2021. A total of 33.33% articles were identified in the ACM Digital Library database and 66.66% articles were identified in IEEE Xplore. See Fig. 3.

The ❸ *validation systems* were carried out by *user study* in the proportion of 22.22%, and we still have 66.67% of systems that were validated by *technical performance,* and 11.11% *demonstration.*

From the point of view of human-drone swarm interaction, we identify 4 scientific articles describing the system by which the swarm interacted with the drone. The drones used in the studies were simulated using the "ros framework" [4], [39], [43] and the "mocap framework" [38] and the drone type was "crazyflie 2.0." This analysis aimed to present information that was selected using a research question *RQ1*.

A. Interaction Modalities and Recognition Technique

To address the second research question, *RQ2*, in II-B on technologies for object recognition in images we present the following information. In our case we will present the interaction modalities that have been identified to send different commands to drone swarms. From our body of work, which covers human-drone swarm interaction, we have identified only gestures, and several Machine Learning algorithms that we will present. This information was extracted from the four steps described.

Therefore, the largest set of gestures for human-drone swarm interaction was 8. The gestures are executed in front of a camera “Logitech HD Pro Webcam C920 of @30FPS”, which are recognized using the algorithm, Machine Learning, DNN (Deep Neuronal Network). The system aims to control a swarm of drones to paint different surfaces of buildings, and the commands it was “one,” “two,” “three,” “four,” “five,” “okay,” “rock,” and “thumbs up” were used to achieve this goal. The drones being simulated and their feedback were observed on the computer [4].

Dandelion Touch proposes a haptic display that is being used for a new type of haptic feedback for VR systems that does not require any wearable or portable interface. To achieve this approach, Fedoseev *et al.* [43], proposes a set of 4 gestures, “moving forward”, “moving backward”, “moving right”, “moving left” and uses an “Oculus Quest Vive Pro” headset.

Swarm Touch, proposes a system that targets human-drone swarm interaction, and receives vibrotactile feedback. The gestures used for swarm control are grouped into two categories, which are “extended state (increasing distance, constant distance, decreasing distance), contracted state (increasing distance, constant distance, decreasing distance)” [44].

In terms of algorithms used in the literature, we find SVM (System Vector Machine) and CNN (Convolutional Neural Network) [45], Robot Bean Optimization Algorithm [41], Body Machine Interface (BoMI) [40], Basic Algorithm [38], DNN (Deep Neural Network) [45]. The articles [39], [41], [43], [44], do not present the recognition algorithm.

B. Data Collection in Drone Swarm Applications

Before reporting on how the data was collected, we first focused on how the researchers validated the proposed systems. Thus, we submitted for analysis the ❹ *type of study* of each scientific paper we analyzed.

Out of the amount of scientific articles we extracted, 88.9% of validated the system through an experimental study. For example, Macchini *et al.* [40], proposes an experimental study for the use of a Body Machine Interface (BoMI) to control a drone swarm. The main observation made in this study is given by the fact that users usually use their hands to control the drones, and therefore used a Leap Motion controller to track the movements of the hand movements. This implemented a Machine Learning algorithm to customize the BoMi interface, based on a rigorous calibration process. The study demonstrated that users received positive feedback on use compared to a remote control.

Another approach, by which the system is validated by experiment, we find in the work of Serpiva *et al.* [4], proposes a drone swarm control system by drawing the trajectory with hand gestures, and gesture recognition is based on the Deep Neural Network (DNN) algorithm. The experiment shows that the accuracy of gesture recognition is 99.7%, which allows the user to have a high accuracy in drawing the drone trajectory compared to the mouse drawing. The system gives the user the possibility to create their own art objects using drone swarms.

The only scientific work that uses a questionnaire is that of Agrawal *et al.* [42] in which they use a drone swarm for emergency scenarios such as search and rescue or fire surveillance. Using artificial intelligence, drone swarms operate autonomously, but nevertheless human intelligence and domain expertise are very important for mission deployment. The proposed system is a meta-model to describe the interactions between human operators and the autonomous swarm. The answers to the questions show that the modeling of interactions through artificial intelligence is supported in drone missions.

The proposed systems are also aimed at interacting with drone swarms, and at the same time being able to receive various information back from these drones. Therefore, our investigations in the literature show that data transmission is performed on PC systems [4], [38], through visual feedback [43], or even tactile feedback [39].

For data manipulation, which also aims at gestural interaction with drone swarms, we find algorithms such as Machine Learning, and Deep Neural Network [4] used to recognize hand gestures. Our analysis also identifies algorithms such as Basic [38], used for the Tic-Tac Toe game. Other algorithms identified in the literature are Body Machine Interface (BoMI) [40], which is used to interact with drone swarms using hand gestures captured by Leap Motion, Robot Bean Optimization algorithm [41], used to search for people using drone swarms in unknown environments, and last but not least, Support Vector Machine and Convolutional Neural Network [45], used to classify tasks that were analyzed using an EEG (electroencephalogram) headset.

IV. Research Implications

Our investigations show that research on the interaction between operators and drone swarms, based on the use of a command and control center has been limited, focusing on only a few types of applications, adopting entirely hand gestures, meanwhile, half of the works investigated in our SLR did not involve participants in the experimental studies presented.

Based on these findings, we formulate several research directions to encourage more work on the interaction between operators and drone swarms, based on the use of a command and control center about our research questions *RQ1* and *RQ2* from Section II-B.

We structure these research directions into the following:

A. *Input Modalities and Interaction Techniques,*
B. *User Studies and Evaluations,*
C. *Involvement of Multiple Drones in Simulations,*
D. *Control and Command Devices and Prototypes.*

For each category, we identify several opportunities for future work.

A. Input Modalities and Interaction Techniques

Our analysis revealed a limited number of interactions, all based on hand gestures, with a total of 15 gestures reported. For example, Serpiva*et al.* [4] proposes a dictionary of 8 gestures: “one,” “two,” “three,” “four,” “five,” “okay,” “rock,” and “thumbs up” for a painting app. Fedoseev*et al.* [43], proposes a set of 4 gestures: “moving forward,” “moving backward,” “moving right,” and moving left” for an application that achieves high-performance haptic rendering of objects in the virtual environment. Tsykunov*et al.* [44] proposes a set of 4 gestures: “extended state (increasing distance, constant distance, decreasing distance),” “contracted state (increasing distance, constant distance, decreasing distance),” for a human-king interaction application in which vibrotactile feedback is received. Unfortunately, these interaction modes have not been evaluated by the user, and consequently, their implementation for drone control remains unknown. Thus, an immediate implication of our findings in relation to the formulated research questions is that more studies are needed to considerably increase the set of gestures for the interaction between operators and drone swarms but at the same time also new input modalities using e.g. wearable devices.

B. User Studies and Evaluations

The previous research direction referred to the importance of input modalities and interaction techniques for the interaction between operators and drone swarms. In the following, we highlight the need for user studies and evaluation of the results, since 55% of the articles presented user studies. For example, the largest number of users involved in a study on the interaction between operators and drone swarms was in the paper [38], in which an experiment was conducted on a game-like application. The second paper in which there were participants in the experiment is Macchini *et al.* [40] in which users’ hand movements are captured using Leap Motion. There were also participants in studies in articles [4], [43] in which seven participants were identified, and the smallest number of users in the studies was 6 [44]. It is therefore necessary to have more users in the studies to be proposed, while at the same time having more methods to evaluate the users. As we have mentioned, in all the studies in which there were participants, we only had experimental status. At the same time, we have to increase the average ages because for the mentioned articles we identify a mean of 8.6 (SD=2.8) and a median of 7.0 participants per study.

C. Involvement of Multiple Drones in Simulations

The use of multiple drones to compose the swarm can be beneficial for more complex missions. We, therefore, present the number of drones that composed the swarm, and then how many swarms were used in our selected articles that focus on the interaction between operators and drone swarms, based on the use of a command and control center. Thus, the largest number of drones was identified in Macchini’s paper *et al.* [40] in which the 20 drones were used for an application in which the drones were controlled by gestures captured by a Leap Motion controller. The articles that presented drone swarms consisting of only four flying devices were [38], [39], [44], and the article that identified the smallest drone formation was composed of three flying devices in Fedoseev *et al.* [43] proposing “Dandelion-Touch” a new type of haptic feedback in VR systems where no portable or wearable interface is required. Therefore, we identify swarms of small drones that are all simulated. Thus, there is an urgent need to form much larger drone swarms, observe user behavior, and also understand how difficult it is to interact with large drone swarms. At the same time extending multiple drone groups, subjected the same user to interact with one or more drones, or even with different swarms he has under management. Using more drones that have a radar device integrated into the ambient intelligence environment [46].

D. Control and Command Devices and Prototypes

The use of devices to control and command drone swarms is necessary because our investigations have uncovered wearable devices such as webcams in the works [4], [38], but also devices such as leap motion [40]. Thus, we suggest that there is a great need for new devices to control and command drones. For example, in Tsykunov *et al.* [44] a smart glove is used to control the drone swarm. Our suggestion is that you can introduce another glove to control one drone in the swarm, and the other to control the whole swarm. Another presented work uses a headset for the interaction between human and drone swarm. An overview of the system functions and control commands for drone-based aerial photography and video, as well as a dictionary of gestures can be found in the scientific article [47]. Therefore, there is an urgent need for new devices to interact with drones but at the same time develop systems that combine known and tested devices.

V. Conclusion

This scientific paper presents a systematic literature review on the interaction between operators and drone swarms based on the use of a command and control center. We highlight that drone swarms are used in different types of applications, but we have not identified a defining one for the scientific community. In terms of drone interaction, only hand gestures are used and feedback is distributed to different wearable devices.

To understand the potential of drone swarms, the results show that there is still a need for contributions, and at the same time to test more interaction modalities, algorithms adapted for drone swarms, and more experimental results. Our investigations have shown that control systems are in their infancy and that few devices are used to form control systems, mainly focused on the visualization of drone information and to a very small extent on drone control.

The proposed implications serve the scientific community to encourage work in the field of drone interaction, which can be applied in different domains whereby we want to emphasize that more work is needed to understand the challenges of interacting with drone swarms, user interaction preferences, and performance in the use of these systems, for which we have proposed four research directions. We hope that our contributions will stimulate the development of new research directions for the interaction between operators and drone swarms based on the use of a command and control center.

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The icons used in Fig. 1 were made by Leremy ("Icon Pack: Drone Personal And Recreational Uses Usage And Applications") from Flaticon (https://www.faticon.com).

Declarations

The authors declare no conflict of interest. Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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