Human-Robot Interaction in UVs Swarming: A Survey

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Abstract

The purpose of this paper is to review research pertaining to the limitations and advantages of User-Robot Interaction for Unmanned-Vehicles (UVs) swarming. We identify and discuss results showing technologies that mitigate the observed problems such as specialized level of automation and human factors in controlling a swarm of mobile agents. In the paper, we first present an overview of definitions and important terms of swarm robotics and its application in multiple UVs systems. Then, the discussion of human-swam interactions in controlling of multiple vehicles is provided with consideration of varies limitations and design guidelines. Finally, we discussed challenges and potential research aspects in the area of Human-robot interaction design in large swarm of UVs and robots.

Keywords: *Human-Robot Interaction, Multi-robot Systems, Unmanned-vehicle, Swarms*

1. Introduction

Swarm robotics, especially controlling swarm teams of multiple UVs, have drawn growing attentions in the recent years. A swarm of mobile UVs can perform a variety of missions that are too complicated, time-critical and cost sensitive for a single UV to undertake. The development of UV system has been conducted for several decades. However, comparing with the extensive existing researches in control and teleoperations of single UV systems, the development of swarm robotics in multiple UVs system are for from mature. This is due to the fact that current applications for swarms of UVs are limited, and the cooperation among UVs teams usually invites extreme complexity.

To put human factors into the swarm team is a relatively new research aspect in the area of swarm robotics. Such a conduct requires an efficient human-swarm interface to facilitate the control and cooperation of UVs teams. However, the major research interest in body of the User-Interface Design (UID) has focused on the design and development of single UV interfaces, while a large swarm of UVs is often required in a specific mission. The development of UID for a UVs swarming, i.e., to control a team of UVs, is becoming more and more critical. The UID for a UVs swarming must support effective interactions and provide good usability, or the design itself may affect perceived workload, and overall performance. Although UID for UVs swarming can share and reuse many elements from single UVs user interfaces, the unique characteristic of swarm systems has to be considered, such as level of automation, autonomous nature of swarm team and switch control of different mobile UV. The functionality and efficiency of the user-Interface will largely influent the performance of the swarm system. Thus, a detailed investigation is required to identify limitations and advantages of recent research findings, and provide possible solutions in the area of human-robot design in UVs swarming. Motivated by the observation, in this report, we will identify and discuss results showing technologies that mitigate the observed problems such as specialized level of automation and human factors in controlling a swarm of mobile agents.

The outline of this survey is as follows: In section 2, an overview of definitions and important terms of swarm robotics and its application in multiple UV systems is presented. In section 3, we discuss human-swam interactions in controlling of multiple vehicles with consideration of varies limitations and advantages. In section 4, we review research findings and existing techniques for Human-Robot interaction design in UVs swarming, and then compare their advantages and limitations with respect to specified situations. In section 5, some recommendations on the design and development of HSI will be discussed, with respect to the existing challenges in this field. Section 6 concludes the survey.

2. Swarm robotics in UVs

Swarm behavior, or swarming, is a collective behavior exhibited by animals of similar size, which aggregate together, perhaps milling about the same spot or migrating in some direction. Particularly, swarming is applied to insects, and this concept is parallels with the shoaling behavior of fish, the flocking behavior of birds, and herd behavior of quadrupeds.

Inspired from the swarm behavior that used to demonstrate the biological manner of social insects, a new research area, which combines the behaviors of social animals with modern robotics, communication technologies and control methods, emerged since nearly three decades ago [1]. The aforementioned research domain is then referred as Swarm Robotics [2]. Swarm robotics is a new research area of coordinating a large number of relatively simple robots. In particular, the teams of robots should have the following characteristics: autonomous with distributed control algorithms/method, capable of local communication, and most important, they should be operated based on some sense of biological inspiration [3].

According to the complexity of the swarm robotics, especially in the aspect of system realization, this research domain can be further categorizes into several subcategories. The earliest research on the classification of swarm robotics can be dated to 1993, when Dudek et al [4] classify the research domain of swarm robotics into five different areas: swarm size, communication range, communication topology, communication bandwidth, swarm reconfiguration and swarm unit processing ability. With different perspectives, many classification criteria had then been proposed successively to summarize the research area of swarm robots into taxonomy of cooperating systems [4]-[6], excepted for the one that was proposed by Parker in [7], where the principle topics that have drawn enough attentions and then generated certain level of research outcomes were used to discriminate the subcategories of swarm robotics. The classification of swarm multi-robot system based on the aforementioned methodologies can be described as follows:

Biological inspiration: Behavior-based control plays an important role in designing multi-robot system [8]. Moreover, biological inspiration is a fundamental factor of the proposed behavior-based control methods. Thus, it is a common way to develop a new cooperative control system for multi-robot swarm based on the examination of different social insects [9].

Communication: According to the definition of swarm robotics, the team of mobile robots should be autonomous without team leaders. Under this constrain, a local decision and inter-agent communication scheme is required in the multi-robot systems. Multi-robot communication has been extensively studied since the emerging of swarm robotics, recent research is focused on network management and connectivity maintenance [10], including fault-tolerate [11] and network recovery [12].

Motion Control and Coordination: In the area of swarm robotics, the motion control and coordination strategy is one of the most rapid developing domains. Studies including path planning [13], architecture-level coordination [14] and formation control of the swarm teams [15] have drawn particular attentions in both academic and industrial societies. In the meantime, several well-know methods, such as nearest neighbor rule [16], artificial potential field [17], have been develop, or adapted to the control and coordination of a swarm of mobile robots.

Task Assignment and Target Manipulation: According to the cooperative nature of swarm robots, to handling the task distribution and assignment with respect to a team of mobile robots and their limitations in function and communication is a vital issue in the development of multi-robot systems. Task assignment has served as an essential research aspect ever since the beginning of swarm robotics. Among all the proposed distributed solutions to the task assignment and task allocation problems, the main focus is given to the market-based method [18], either depend on full [19], [20] or limited [21] information of the network, market-based methods can efficiently and dynamically assignment each task/spot to an optimal robot. In the mean time, a swarm of robots gives a possible solution for target manipulation, where the single robot system was proved to be impossible to handle. Extensive research on this subject was carried out by the GRASP Lab., rooted in the University of Pennsylvania [22], where N. Michael conducted several researches in the manipulation and target transportation both with multiple ground and aerial robots [23].

With the rapid development of swarm robotics in the aforementioned research domains, a particular interest is focused on the design and application of swarm robotics in multi-vehicle systems, i.e., large teams of unmanned vehicles that may perform certain tasks which are impractical or even impossible for human or single vehicle to undertake. Typical applications include multi-vehicle planetary exploration [24], and transportation of supplies in hazardous environment [25].

Unmanned Vehicles can be considered as the special types of multi-robot systems, which are mainly used in military applications. Typically, there are three different types of Unmanned Vehicles: Unmanned Aerial Vehicles (UAVs), Unmanned Ground Vehicles (UGVs) and Unmanned Underwater Vehicles (UUVs). The criteria for the discrimination are based on the domains of system applications.

Unmanned Aerial Vehicles (UAVs) [26] is an aircraft that is flown by a pilot or a navigator (or Combat Systems Officer, CSO) depending on the different applications. However, without a human crew on board the aircraft. Their largest uses are in military applications. UAVs are often preferred for missions that are too "dull, dirty, or dangerous" for manned aircraft. A swarm of military UAVs can perform reconnaissance as well as attack missions [27], and the developing applications in civil applications, such as firefighting or nonmilitary security work.

Unmanned Ground Vehicles (UGVs) [28] is often referred as a team of military robots used to augment the soldiers' capability. Such robot teams are generally capable of operating outdoors and over a wide variety of terrain, functioning in place of humans. The UGVs system can be further divided into two different categories: Teleoperation and Autonomous, according to the types of guidance. Nevertheless, for a swarm of UGVs, depending on the complexity of interactive operations, Autonomous or Semi-Autonomous are usually adopted.

Unmanned Underwater Vehicles (UUVs) [29] is an emerging research area that closely followed the recent development of submarine systems. UUVs have been used by U. S. Naval forces in an expanding variety of roles, including inspection of coastal waters for mines and other hazards [30].

The development of UV system has been conducted for several decades. However, comparing with the extensive existing researches in control and teleoperations of single UV systems, the implementations of swarm robotics in multiple UVs system (or teams of UV) are for from mature. This is due to the fact that current applications for swarms of UVs are limited, and the cooperation among UVs teams usually invites extreme complexity.

To date, several prototypes or experimental systems have been developed to apply swarm robotics in the area of Unmanned Vehicles. The key of such development is to design coordination and cooperation strategies to stimulate system performances by utilizing behavior-based inspiration. Moreover, the development of swarm robotics based UVs systems should appreciate the different levels of autonomous that the systems require. In the recent decade, growing interests have been observed in the implementation of swarm robotics into UVs systems, several methods and prototypes can be find in recent publications [31]-[35], [37]. In [31], a swarm of small UAVs (Miniature Helicopters in this case) is used to conduct cooperative search tasks in the subject of Wilderness Search and Rescue (WiSAR). The updating mechanism of grid-based probabilistic maps based on recursive Bayesian processes is introduced, and the information exchange method for the coordination of the UVs swarm is then presented. In [32], Han et al. proposed a behavior-based decentralized control strategy for unmanned aerial vehicle (UAV) swarming by using artificial potential functions and sliding mode control technique. In this strategy, individual interactions for swarming behavior are modeled using the artificial potential functions. The idea of controlling a swarm of UGVs using a single UAV is proposed in [33], where the UAVs is fully autonomous and controlled using Sugueno Fuzzy Logic, while the inter-UGVs interaction in the swarm is by means of Potential Functions. The author further presented a strategy for organizing swarms of unmanned vehicles into a formation by utilizing artificial potential fields that were generated from normal and sigmoid functions in [34], where the proposed artificial potential functions and limiting functions are combined to control swarm formation, orientation, and swarm movement as a whole. In [35], the authors we proposed a new approach for cooperative swarm coordination of multiple combat UGVs, based upon the observation on the immune system (a remarkable example of highly scalable distributed system [36]). In 2007, Hou et al. presented a number of behavior-based rules for team cooperation and navigation of UUVs [37], the development of such rules are also based on animals' typical group behavior, which is referred as Schooling for underwater lives. In the proposed method, the impact of water flow on the performance of the UUVs swarming has been taken into consideration.

According to the aforementioned literatures, to control a swarm of UVs sometimes requires uniqueness with respect to different specification of system requirements, and most important, the Level of Automation (LOA) of the target systems. This raises the problems of Operator-System Interactions (OSI) , and ultimately, User-Interface Designs (UID) for the UVs Swarming.

3. Human-Robot Interaction in Swarms

Human-Robot Interactions can be defined from the perspectives of human interference and the operator's participation in a given task. Either by the level of automation (LOA), or by the types of operator interacting with the UVs swarming systems.

3.1. Operator's Participation

Humans play a variety of roles while participating in given tasks with a swarm of UVs, such roles including: planning, teaching, monitoring, intervening, and learning [38]. Typically, these roles occur in the temporal order described, and may repeat throughout the task. Sheridan [38] describes these roles in sequence as follows: 1) Planning the course of action before the automation is activated. 2) Instructing the computerized technology to perform a task in a particular manner. 3) Monitoring the instructed automation to be sure it goes as planned. 4)

Intervening, when necessary, to adjust or correct the automation. 5) Learning from the performance and outcomes of the automation in order to improve planning for future interactions.

In the five steps of operator's action, Planning ahead of time is vital for the system output. In UVs swarming system, Planning may be referred as task assignment and vehicle's distribution, and such actions are critical for the future performance of the entire system. The following steps, e.g., Instruction, Monitoring and Intervening, may depend on the Level of Automation (LOA) in a particular system. Step 5 is usually an optional feedback manner in the Human-Robot Interaction (HRI).

3. 2. Level of Automation (LOA)

When controlling a swarm of UVs, the amount and types of human interactions with the automated technology must be considered in order to determine the appropriate LOA to employ. Parasuraman et al. have defined human interaction with automated technology in terms of ten "levels of automation of decision and action selection," that are based on four stages of human information processing (cf. [39]).

1) Information acquisition. 2) Information analysis. 3) Decision and action selection. 4) Action implementation.
However, with consideration of the particular characteristics in UVs swarming, the level of automation can be re-defined into a four-layer structure, as shown in Fig. 1.

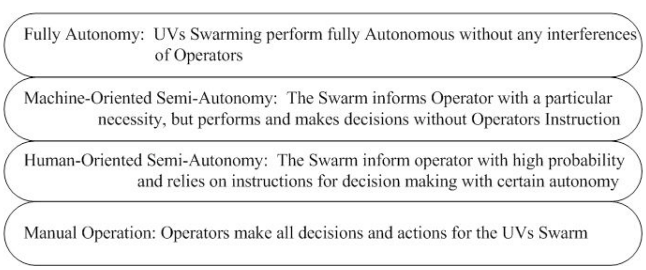

Fig. 1. The Levels of Automation (LOA) for UVs Swarming

There are risks and benefits associated with each LOA in terms of the associated mental workload, reliance on the automation and the human operator's level of SA [39]. Therefore, it is vital to adopt an optimal LOA that provides not only a balance of human workload between challenging and manageable, but also a level of SA sufficient to meet task performance goals. For instance, Machine-Oriented Semi-Autonomy excludes the human operator from making decisions and taking actions; thus, the swarm left humans only the monitoring role, which can lead to the "Lack of emergency actions" of the human operators when an error occurs. Deference Levels of Automations requires different interaction frameworks in Operator-System UVs Swarming architectures. And a few researches have been conducted in such an area.

3. 3. Human-Robots Interactions in UVs Swarming

The HRI problem can be defined as understanding and shaping the interactions between one or more humans and one or more robots. Interactions between humans and robots are inherently present in all of robotics, including autonomous robots. Apparently, HRI problems are not restricted to a single human and a single robot, though this is certainly one important type of interaction. Nevertheless, compare to the numerous research outcomes in Single human-Single Robot Interaction (See a comprehensive review in [40]), Human-Robots Interaction in UVs Swarming, or so called Human-Swarm Interaction (HSI) is a new developing research domain, and is far from mature. In general, with a certain level of automation, to control a swam of UVs is not as much different as controlling one single robot, this may due to the fact that certain level of automation may enable the multi-vehicle system enough autonomous and the capability of self-organization, such that the swarm can be treat in whole as a single operative device. Therefore, one human operator may be good enough for interacting with such a system and perform a desired task in such case. For example, UVs swarm that fells into the LOA category of Machine-Oriented Semi-Autonomy is manageable with minimal supervision, and such supervision can be relied on a single human being. Even in some Human-Oriented Semi-Autonomy systems, one operator may be sufficient if the decision and action of the system only need occasional assistance of the operator. In [41], MIT Computer Science and Artificial Intelligence Lab., associated with iRobot Corporation, presented strategies to maintain, program and interact with swarm without having to handle them individually. The swarm of UVs is in the category of Human-Oriented Semi-Autonomy, it uses methods to allow user to control individual robot or the entire swarm; both of which is against the notion of emergent intelligence.

Bruemmer et al. argued that HRI for multi-robot system should be inspired from nature and should promote swarm intelligence [42]. The research later deviates slightly from the notion of swarm intelligence: "Unlike in the insect world, the robotic system must interact with human operators. At a minimum, this interaction includes responding to operator directed tasking and status reports on task progress". However, challenges may still reside even we chose higher levels of automation. As

Dudenhoeffer et al. suggested, with high level of automation where the operator serves mainly a monitoring role, situation awareness may be negatively impacted [43]. Their study also suggests that emphasis on monitoring alone ignoring collaboration roles in multi-robot interaction poses a significant problem to the overall swarm due to degradation of situational awareness. In spite of the existing technologies and the development of robotics, researchers still hold a pretty negative view to the design of HSI [44]-[46]. In [44], the importance of HRI in rescue robotics is emphasized, while the author argued that the demands of the task, the form factor of the robot, and the need to protect robot operators requires at least two operators. And R. R. Murphy further claimed that the present day robotics technology is not able to operate autonomously and hence the HRI is a key component in the development of the human-robot team [45].

A detailed illustration of HSI has been proposed in [47], where the authors explore the topic of human–robot interaction (HRI) from the perspective of designing sociable autonomous robots (robots designed to interact with people in a human-like way). The classification of systems on the basis of HRI is presented as follows: robot as tool, robot as cyborg extension, robot as avatar and robot as sociable partner. Each is distinguished from the others based on the mental model a human has of the robot when interacting with it. And several other works, such as in [48]-[50], has give inspirations in the design of HSI in different perspectives, which associated with the development of HRI.

The aforementioned researches in the area of HSI suggest that the systems that only offer monitoring roles to the user, i.e., in the upper two levels of automation is not like to be succeed, since monitoring alone makes users less participative in UVs swarming. On the other hand, an interaction that gives a complete control to the user, i.e., Manual Operation in Fig. 1 suffers from human errors and the user workload is very high.

4. Challenges and Solutions

The development of HSI has been strongly constrained, due to the immaturity of several related fields, such as swarm robotics and inter-agent communication and cooperation. Nevertheless, a user-friendly and efficient interface may enhance the performance of the entire system and compensate the complexity of the operation schemes.

To design an acceptable HSI, the specifications of each individual swarm system has to be carefully identified, and then the proposed detailed design has to match the specifications as well as particular requirements. Although the aforementioned principles indicate that the experiences and innovative thoughts play an important role in developing HSI, some common methodologies can still be derived from a variety of proposed systems. In this section, some recommendations on the design and development of HSI will be discussed, with respect to the existing challenges in this field.

4.1. Communication Architecture and LOA

Communication architecture is the vital part in the system architecture of each swarm system, and may be varied from case to case, depends on the scale of the team, number of operators and the main objective of the system. However, some common functions have to be carried by the system without exception, such as inter-agent communication, human-swarm communication, input/ output, etc. For each of these common functions, certain techniques could be widely adoptive, and the whole system is to be optimized upon the utilization of these techniques.

4.2. Inter-agent communication

As mentioned in section 2, the team of mobile robots should be autonomous without team leaders. Under this constrain, a local decision and inter-agent communication scheme is required in the swarm systems. Inter-agent communication has been extensively studied since the emerging of swarm robotics, a number of techniques have been adopted, including WiFi, ZigBee, Inferred and Bluetooth. On the network level, the most popular communication scheme is multi-hop end-to-end communication without infrastructures (also known as ad hoc mode) [10], which closely match the autonomous nature of the swarm system. Therefore, for the network level of the system architecture, ad hoc network will be the optimal choice under most circumstances. Nevertheless, cellular mode can also be selected if the infrastructures are available, e.g., the swarm system is about to be operated in urban area and on the ground, where the signals and network conditions is stable for cellular communication. Meanwhile, the specific communication techniques to be adopted should match the requirements and the operation environments of the swarm systems.

4.3. Human-Swarm Communication

Apparently, Human-Swarm Communication (HSC) is a fundamental function for the HSI. It is the basis of any Human-Swarm interactive and input/outputs functions. With respect to the fact that there is no leader in Swarms, the HSC should be able to build direct communication links between operators and each mobile agent in the swarm team. However, most Human-Swarm interactive systems require teleoperation with enlarged communication range, which can be up to kilometers, or even thousands of kilometers in the case of global wide teleoperation. So that satellite communication is often suitable for HSC, and the requirement of direct links between operators and distinctive agents will result in two sets of communication devices in each mobile agents in the swarm team. Evidently, it is not an economical or even practical way to design the communication system.

It is suggested that, to avoid redundant communication devices and to enhance the system performance, some mobile agents can be selected as routers, which are able to communicate directly with the operator, and build multi-hop communication link between operators and every other mobile agents. The selected routers can also be called the "virtue leaders", and act as an information hub in the whole system. It is worthwhile to mention that the number of the selected routers in the swarm system can be varied, depends on the required level of robustness.

With a satisfactory communication system, the basis structure of the HSI can be developed with the assumption that each parameter, order and feedback data can be transferred without any problem, which means the network level is transparent to the service level of the system. Upon such assumption, the critical part in HSI design will turn to be the level of automation (LOA) to be determined with respect to the specifications of each distinctive UV swarming system.

4.4. Level of Automation (LOA) Determination

As discussed in sectionIII, there are risks and benefits associated with each LOA in terms of the associated mental workload, reliance on the automation and the human operator's level of SA, and it is vital to adopt an optimal LOA that provides not only a balance of human workload between challenging and manageable, but also a level of SA sufficient to meet task performance goals. It is also challenging to balance the system's autonomous manner with the amount of interferences from human-operator, e.g., if a major part of control in each mobile agent is conducted by operators' order, then it should not be considered as a swarm system in the first place.

The determination of LOA is case sensitive, and different UV swarming systems may require totally different LOA to successfully execute the tasks. For instance, a swarm of sensor nodes that performs a surveillance function requires only minimal human operations (Higher LOA), while a team of mobile robots to explore an unknown area may need the operator to take over the control of each robot whenever it encounters unexpected situation (Lower LOA). The ideal LOA is said to be the one that functions autonomously while providing users with a method to inject knowledge and guidance so as to improve the performance of the system. And these rules should be followed in the design of User-Interfaces in a real UVs swarming system.

It is also suggested that the concept of autopilot in aviation could be adopted in LOA determination of Human-Swam system. So that the swarm team can be fully autonomous in normal situation, while human operator can interval and adjust the LOA whenever the system is in emergency or tricky situations (Mirror the situation where pilot disengages autopilot and/or autothrottle when the airplane is takeoff/ landing or in emergency).

Once the LOA of the swarm system is determined, the modules of the HSI can be designed. Although the types of modules in the swarm system can be varied from case to case, some core modules will be necessarily required in most swarm system.

5. Conclusion

A review research is conducted in this paper to identify the limitations and advantages of User-Interface Design for UVs swarming. We identify and discuss results showing technologies that mitigate the observed problems such as specialized level of automation and human factors in HSI design of controlling a swarm of mobile agents. This survey includes an overview of definitions and important terms of swarm robotics and its application in multiple UV systems, the discuss human-swam interactions in controlling of multiple vehicles with consideration of varies limitations, design guidelines and research findings. Furthermore, we discussed challenging problems and possible solutions in the area of user-interface design in swarm of UVs and robots. Based on the discussion, a number of recommendations are proposed in the area of system architecture, module designing and evaluation methodologies. The purpose of this survey is to perform an insight evaluation of the current development in the area of HSI design UVs swarming, and to provide a few guidelines for its future design and development.

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