A Systematic Review of Swarm Robots

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Authors' contributions

This work was carried out in collaboration among all authors. Author IO designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors IR and IG managed the analyses of the study. Authors OO and OJ managed the literature searches. All authors read and approved the final manuscript.

Systematic Review Article

ABSTRACT

Advances in robotics have paved the way for a novel approach of organizing large numbers of robots, otherwise referred to as multi-robots. Multi-robots can either be homogenous or heterogeneous. Nevertheless, a group of autonomous and relatively homogenous robots that interacts with one another as well as with their environment is referred to as swarm robots. Swarm robots are biologically inspired by natural swarms as found in animal societies such as birds and fishes as well as social insects such as honey bees, wasps, termites and ants. Hence, they exhibit certain properties which are similar to those found in these creatures such as aggregation, self-organization, foraging as well as flocking. Swarm robots work together to achieve a desired goal, which is usually too complex for a single robot to accomplish. They are typically characterized by simplicity of individuals, fault tolerance, autonomy, parallelism, high reliability, scalability as well as robustness. They can be used for mining, military, medical and agricultural activities. They can also be used for search and rescue missions, toxic waste cleanup, and for piling sandbags along coastlines in preparation for floods or hurricane. Nevertheless, swarm robots are plagued with the

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stigma of widespread, interference, uncertainty, safety and lack of reliable communication. Furthermore, studies in swarm robotics are practically limited to virtual reality simulations. Hence, the principles of swarm robotics are rarely applied to real-life problems. It is against this background that this study systematically explores swarm robots. This study reviewed eighty literatures relating to swarm robots. These literatures were obtained from journal articles, technical reports, books, and conference proceedings. The selection of these literatures was based on their relevance to the research problem. This study revealed that the application of swarm robots to real life problems would promote the development of systems that are robust, fault tolerant and scalable.

1. INTRODUCTION

Several creatures move in groups or swarms of few to more than millions of individuals. Swarming is mainly applied to animals and social insects such as honey bees, wasps, locusts, termites and ants. Typical examples of animals that exhibit swarming behaviour include fishes, turtles and birds. Interestingly, swarming is referred to as flocking or murmuration in birds, herding in tetrapods such as turtles and shoaling or schooling in fishes. Characteristically, these creatures are usually of the same size, and they move together in search of food and shelter because discrete individuals have a higher chance of surviving in the group than when alone. They support and protect themselves effectively in the swarm. They respond to the speed of their counterparts and avoid collisions within the swarm [1]. Also, they communicate with one another while maintaining a decentralized network and exhibiting self-organized behaviour [2,3]. Besides, animals and insects are not considered overloaded even as more individuals join the swarm. These creatures also exhibit stigmergic communication. For instance, ants lay pheromone on the ground. At the same time, wasps use secretions to signify the presence of danger to their mates and indicate the paths to their food sources. The goal of insects and animals in swarms is to ensure that the process of solving problems is more efficient through cooperation and division of labour. Fig. 1 shows examples of diverse creatures in swarms.

The interactions exhibited by the animals and social insects in swarms have been a source of inspiration to many kinds of research in swarm intelligence [8,9]. Hence, Tan and Zheng [10] emphasized that swarm intelligence is a soft bionic of natural swarm. The term swarm intelligence is a concept proposed by Gerardo Beni in the 1980s [11]. It is a branch of computational intelligence that is composed of a population of simple agents interacting locally with the environment and one another [12]. Tan and Zheng [10] define swarm intelligence as a system that consists of a group of individuals autonomously controlled by a clear set of rules and local interactions. Bonabeau et al. [13] view swarm intelligence as any attempt to design algorithms or distributed problem-solving devices that are inspired by the collective behaviour of social insects and other animal societies. From the definitions above, we deduced that swarm intelligence is a branch of computational intelligence that is composed of a population of relatively simple, homogenous and autonomous agents that communicate locally with one another and their environment while adhering to simple behavioural rules.
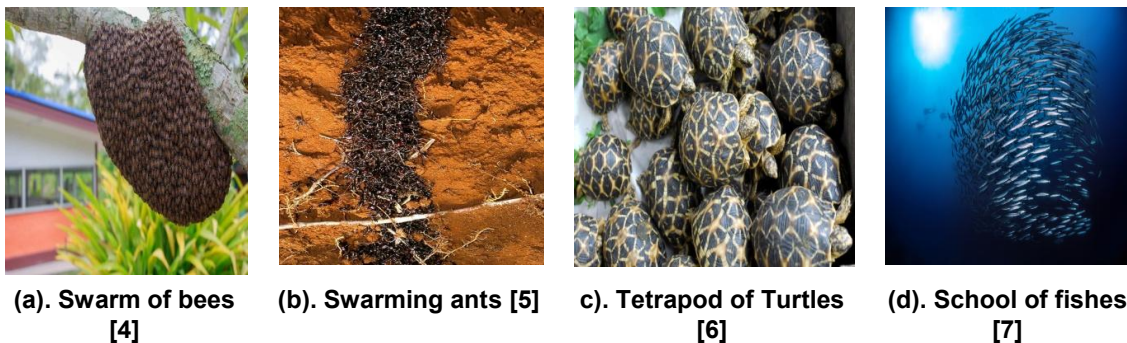

(a). Swarm of bees [4]   **(b). Swarming ants [5]**   **c). Tetrapod of Turtles [6]**   **(d). School of fishes [7]**

Fig. 1. Diverse social insects and animals that exhibit swarming behaviour

The process of applying swarm intelligence techniques to the co-ordination of the activities of physical robotic devices interacting with one another and their environment is referred to as swarm robotics [14]. Gupta et al. [14] define swarm robotics as a technique in which a group of autonomous and homogenous robots work in a synchronized manner to complete a specific task. Sahin [8] describe swarm robotics as the study of how a large number of relatively simple and physically embodied agents are designed in a way a desired collective behaviour can emerge from the local interactions among the agents and their environment. Swarm robots are also a group of relatively identical and small robots with little capabilities individually with which they work together to achieve a desired global goal with the help of robot-robot and robot-environment interaction. Remarkably, the robots in a swarm communicate with one another using local communication that can be achieved via wireless transmission such as infrared and radio frequency [15,16].

The advantages of swarm robots outperform those of individual robots. For instance, swarm robots accomplish tasks concurrently and hence more quickly than individual robots because tasks can be too difficult for a single robot to accomplish. They are cheaper to design, manufacture and maintain when compared to individual robots [10]. The robots in a swarm are robust, reliable and more scalable than individual robots.

Swarm robots (SR) have the potential to be used in medicine for tasks that require miniaturization.

By this, they can be used in surgery, early diagnosis and treatment of cancer cells as well as for monitoring patients' health. Besides, SR can be applied in mining, geological survey, agricultural foraging, welding, painting, military activities and oil spill cleaning [17,18]. They can also be used for search and rescue missions, harvesting, grass mowing and toxic waste cleanup. Despite the potential benefits of swarm robots, they are plagued with the stigma of widespread, interference, uncertainty, safety and lack of reliable communication.

Furthermore, most studies in swarm robotics are limited to virtual reality simulations in Computer Science [10,19,20]. Hence, the principles of swarm robotics are rarely applied to real-life problems. It is against this background that this study systematically reviews swarm robotics.

The remainder of this paper is structured as follows: Section 2 describes the research methodology. In section 3, we summarize the shreds of evidence from the selected studies and describe the strength and limitations in Section 4. In section 5, we provide the conclusions and discuss future work.

2. RESEARCH METHODOLOGY

This study systematically identifies, analyzes and interprets studies relating to swarm robots. This is to obtain evidence on some of the principles of swarm robots. We adopted the 5-step approach proposed by Khan et al. [21] as shown in Fig. 2.
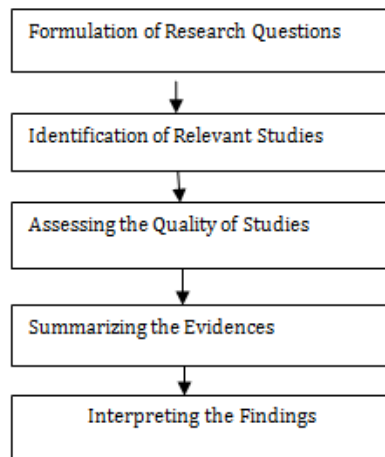

Fig. 2. The research framework [21]

2.1 Formulation of Research Questions

The research questions below were formulated for this study. The goal is to understand and summarize the empirical proofs of the state-of-the-art studies on swarm robots. The research questions, in our opinion, will assist researchers in identifying areas for further research.

RQ1: What are swarm robots?
RQ2: What are the properties exhibited by swarm robots?
RQ3: What are the benefits of swarm robots?
RQ4: What are the challenges of swarm robots?
RQ5: What are the swarm robotic platforms?
RQ6: How are tasks allocated among swarm robots?
RQ7: What is the interaction between humans and swarm robots?
RQ8: How is information exchanged among robots in a swarm?

2.2 Identification of Relevant Studies

This stage involved an extensive search of literatures that are related to swarm robotics. The search was conducted between March-December, 2019. Six electronic databases, namely CiteseerX, IEEE Explore, Web of Science, Springerlink, Science Direct and Google scholar were used for this process. Besides, the Google search engine was searched for documents and WebPages containing appropriate information for the study. We conducted a search of titles, abstracts and keywords using the following keyterms "swarm robots", "swarm robots properties", "benefits of swarm robots", "swarm robotic platforms", "limitations of swarm robots", 'task allocation and swarm robots', ''human swarm interaction" and "information exchange in swarm robots". Thereafter, the full texts of the literatures were assessed. Studies that were not written in the English Language were excluded from the study. Literatures that were not related to the research questions were also excluded from the study. In addition, papers without bibliographic information such as publication date/type, volume and issue

numbers were excluded from the study. A total of 101 literatures were obtained from the search process. Also, the search process involved a manual search of the bibliographies and references of the selected papers. At the end of this process, 25 papers were found to be related to the research questions. Hence, a total of 126 literatures were identified as relevant studies for this systematic review.

2.3 Assessing the Qualities of the Studies

The 126 relevant literatures previously identified were examined to determine their qualities. The qualities of these literatures were determined based on the following quality assessment checklists.

1. Are the objectives of the identified literatures within the defined scope of the research questions?
2. Are the objectives of the identified literatures clearly defined?
3. Are their methodologies appropriate?

Each of these questions had only three optional responses, which include Yes, No and Undecided. The responses were scaled as shown in Table 1.

The quality of each of the literature was determined by finding the percentage of the scores based on the quality assessment scale in Table 1. We agreed that literatures with scores less than 50% should not be considered for the systematic review. At the end of this process, 46 literatures were excluded from the study while only 80 papers were considered as relevant for the systematic review. Three (3) papers were obtained from CiteSeer X, four (4) papers were obtained from IEEE Explore and two (2) papers were selected from Science Direct. Four (4) papers were selected from Web of Science, twelve papers (12) papers were selected from Springerlink and nine (9) papers were obtained from Google scholar while forty six (46) papers were obtained from the Google search engine.

Table 1. The quality assessment scale

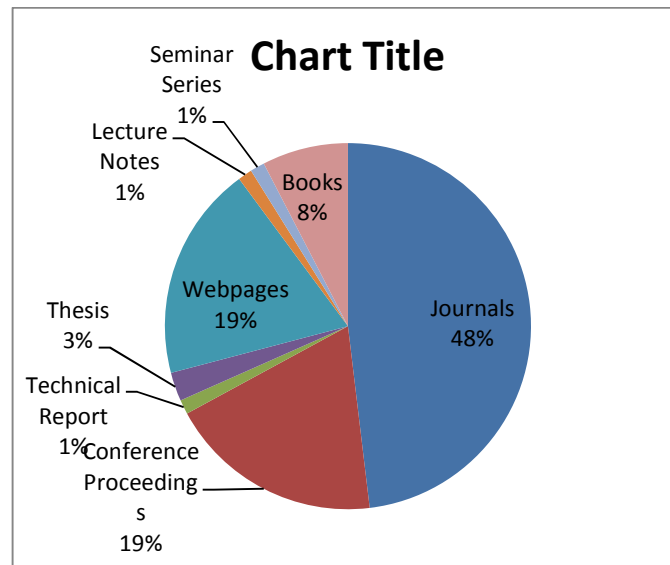| Response	Scale
Yes	1
No	0
Undecided	0.5

Fig. 3. Percentage distribution of the selected studies

The literatures selected included forty journal articles (40), six (6) edited books, fifteen (15) conference proceedings, one (1) technical paper, fifteen (15) WebPages, one (1) lecture note, one (1) seminar paper and one (1) doctoral thesis. The percentage of the selected studies is as depicted in the pie chart in Fig. 3. The selected studies were published between 1983 and 2018.

2.4 Threats to Validity

The studies were chosen based on the following search strategy described previously

(a) Use of literature databases,
(b) Selection criteria, and
(c) Quality criteria.

The key terms corresponding to the specified research questions was used to identify relevant studies for this review. However, it is possible that relevant studies were still omitted with the key terms that are related to the research questions in their titles, abstracts or keywords. Hence, a manual scrutiny of the references of all the extracted studies was carried out to identify those studies that were missed out during the initial search.

3. RESULTS AND DISCUSSION

This section summarizes the evidences from the relevant literatures by providing the answers to each of the research questions.

3.1 RQ1: What are Swarm Robots?

Swarm robotics is a relatively new research area that is inspired by biological systems such as insect colonies, flocks of birds and schools of fishes [22]. There is no universal and formal definition for swarm robotics [23]. Despite this, numerous authors have provided diverse definitions for this term. Navarro and Matía [24] defined swarm robotics as a discipline of multi-robotics that comprises a large number of robots that are organized in a distributed and decentralized way. Mohan et al. [25] define swarm robotics as the use of swarm intelligence principles to a group of robots. Ben-Ari and Mondada [26] view swarm robotics as a distributed approach to robotics which mimics the mechanisms inspired by the behaviour of social animals. For Sahin [8], swarm robotics is defined as the study of how large numbers of relatively simple and physically embodied agents can be designed in a way that a desired and similar behaviour emerges from the local interactions among the agents and between the agents and the environment. Podevijn [20] views swarm robots as a team of large, self-organised and homogenous robots which carry out complex tasks by interacting and cooperating with one other in a decentralized manner. From the aforementioned, we defined a swarm robot formally as a group of autonomous, decentralized and relatively homogenous robots which do not have a global understanding of their immediate environment but cooperate with one another to achieve a desired goal.

3.2 RQ2: What are the Properties of Swarm Robots

The property of a system refers to the state of the system [27]. Based on this definition, te following are the properties of a swarm robotic system.

i. **Robustness:** In Snyder's terms [28], robustness is defined as a system's impassiveness or ruggedness towards randomly occurring changes within its environment. Meepetchdee and Shah also defined the concept of robustness as the ability of a system to perform its designated tasks despite disturbances [29].

ii. **Autonomous:** Swarm robots are autonomous because they are independent of one another and can interact with themselves and their environment. There is neither a central control nor hierarchy in a swarm robotic system. This decentralized property of swarm robot distinguishes them from traditional robots [30].

iii. **Scalability:** Scalability, according to Bayindir and Sahin [31] is the ability to expand a self-organized mechanism, to support more substantial or smaller numbers of individuals without impacting performance considerably. Hence, the addition or removal of more robotic systems in the swarm will not affect the density of the swarm as long as individual robots still interact with approximately the same number of robots that are within the sensing and communication range. Scalability is usually enabled by local sensing and communication in swarm robotics [32].

iv. **Homogeneity**: Swarm robots are relatively homogenous. However, Dorigo et al. [17] noted that some robot swarms are heterogeneous, but these sets of robots are homogenous at the level of interactions.

v. **Local Communication:** Robotic swarms do not have a global understanding of their environment, just like natural swarms. Hence, the interaction between individuals in the swarm is based on the concept of locality. This implicit model of communication is referred to as stigmergy [33].

vi. They do not rely on pre-existing infrastructure. Hence, human operators are usually required to operate swarm robotic systems.

vii. **Cooperation:** The individuals in a robotic swarm are relatively incapable; hence they cooperate to achieve a common goal. Furthermore, cooperation is required in swarm robotics because the tasks at hand are usually too difficult to be carried out by a single robot.

viii. **Flexibility:** Flexibility as defined by Bi et al. [34] in the context of robotic systems is the ability of a system to perform different tasks.

ix. **Fault Tolerance**: According to Ledmi [35], when a hardware or software failure occurs in a system, it usually results in a fault. However, the process of allowing the system to continue to perform its functions in the presence of these faults is referred to as fault tolerance.

x. **High Speed:** Swarm robots accomplish tasks concurrently and hence more quickly than individual robots.

xi. **Aggregation:** As the name implies, aggregation refers to the process of grouping the individuals of a swarm into a cluster without using any environmental clues [36]. Aggregation is a very fundamental property in natural swarm [37]. It is also crucial in swarm robotics because it plays an essential role in co-operation, communication and interaction.

xii. **Dispersion:** Dispersion, as its name implies, is the spreading out of the swarm robots uniformly while still connected through a communication channel.

xiii. **Safe-wandering**: This is the ability of the swarm robots to move about while avoiding collisions at the same time.

xiv. **Self-organisation or assembly:** Self-organization is often seen in natural swarms when a pattern is formed at a global level from the interactions of lower systems. They usually do this to protect themselves from the attack of predators and to avoid a collision. In the swarm robotic parlance, self-organization refers to the ability of the swarm robotic system to spontaneously arrange its components or elements in a non-random order without the help of an external agent and under suitable conditions. Self-assembly in swarm robots is defined as the process in which a group of robot comes together to form a temporary body structure that is capable of performing a task [38]. Self-organization in natural and swarm robots is illustrated in Fig. 4.
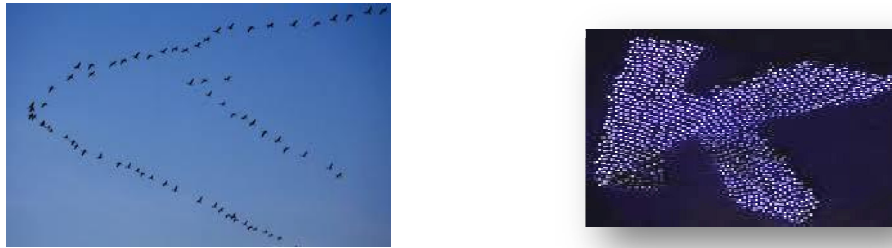
Fig. 4. Self organization as exhibited by birds and kilobot swarm [39,40]

xv. **Foraging:** This property is inspired by ants while searching for food sources. Similarly, foraging in swarm robots refers to the ability of a group of robots to search for and retrieve food items to their nest.

xvi. **Flocking:** Flocking in swarm robots is inspired by animals and insects that move in groups as a single entity such as birds, fishes and ants. One of the significant reasons for flocking in animals is for protection against predators and warmth. Swarm robots also mimic this behaviour. Nevertheless, Masehian and Royan [41] emphasized that each robot in a flock adjusts its speed and move along with other robots in the flock while sustaining a pre-determined formation and avoiding collision with other robots in the swarm.

xvii. **Collective object transportation:** This property is also inherent in social insects such as ants when they work together to move a large object intact over different terrains and back to their nests while maintaining consensus about travel direction [42]. This type of property is also found in swarm robots. Collective object transportation in swarm robots is defined as the coordination and synchronization of pushing and pulling forces by a group of autonomous robots to transport items that cannot be transported by a single agent [43].

3.3 RQ3: What are the Benefits of Swarm Robots?

Swarm robotics systems are well suited for real-world applications such as medicine, environmental exploration such as underwater or extra-terrestrial planetary exploration, oil spill cleaning, surveillance, search and rescue mission, demining, agriculture and construction [17]. However, their applications are relatively limited to virtual reality simulations. Despite this limitation, this section appraises the application areas of swarm robots to provide information that can assist humans in solving practical and real-life problems.

3.3.1 Medicine

Majid al-Rifaie [44] emphasized that swarm robots can be used to achieve improved precision in the location of cancer cells in human anatomy. According to Majid al-Rifaie [44], microrobots have been used to improve endoscopic procedures of the gastrointestinal tract by providing valuable information about significant pathologies such as bleeding, malignancy or precancerous conditions in the gastrointestinal system. This form of medicine is referred to as nanotechnology.

3.3.2 Agriculture

The goal of swarm robots in agriculture is to improve agriculture by providing a smart and cheap approach to agriculture. For instance, Dorhout developed Prospero an autonomous micro-planter from an off-the-shelf platform called boe-bot [45]. Besides, Saga (Swarm Robotics for Agricultural Applications), a swarm of drones, has also been designed to monitor weed infestations and the status of crops [46]. Saga takes its inspiration from bees and ants. Also, the Kilobot swarm robots are used for pollinating flowers and for stacking sandbags along the coastline in preparation for flood or hurricane. Prospero is as shown in Fig. 5.

3.3.3 Search and rescue missions

Some tasks are too dangerous for human beings. Search and rescue mission is an example of such tasks. Search and rescue mission entails the search for people who are in danger or distress. Search and rescue missions are usually done for those that are trapped in
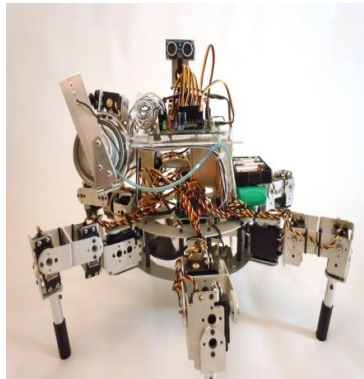
Fig. 5. Prospero [47]

diverse forms of accidents such as explorers trapped in caves or mountains and people trapped in collapsed buildings or earthquake. In order to avoid injuries during this mission, swarm robots can be deployed. For instance, polybot, swarmbot and M-TRAN are designed for search and rescue missions [48].

3.3.4 Cleaning of oil spills

Swarm robots can reduce the cost and time for cleaning oil spills. An example of swarm robots that have been used for oil spill cleaning is sea swarm. Seaswarm is an autonomous system developed by the Senseable group at the Massachusetts Institute of Technology [48]. The primary goal of sea swarm is to skim the ocean and remove oil spills. Communication is achieved in the swarm through Global Positioning System (GPS) and Wireless Fidelity (Wifi). According to Lev [49], sea swarm prototype has been tested at Boston's Charles River.

3.3.5 Exploration

Several swarm robots have been applied to exploration. For instance, Marsbees has been designed by researchers at the University of Alabama, Huntsville, George Washington University, USA and Tokyo University, Japan. Marsbees is the size of a bumblebee, and its goal is to explore the planet Mars [50]. Marsbees has a flapping wing with which it flies to collect data over the surface of the Mars. Furthermore, the CoCoRo swarm is used for in-depth underwater exploration.

3.3.6 Military

According to McMullan [51], the US Defense Advanced Research Project Agency (DARPA) is working on a project tagged Gremlins. This micro drone has the size and shape of a missile. The target of this agency is to use Gremlins for reconnaissance over vast areas. Also, the US Navy Office of Naval Research has designed a drone swarm called Low-Cost UAV (Unmanned Ariel Vehicle) Swarming Technology (LOCUST) to protect a high-value ship from an external craft.

3.4 RQ4: What are the Challenges of Swarm Robots?

Swarm robots are plagued with diverse challenges despite their numerous applications [22]. Some of the challenges of swarm robots are discussed below.

3.4.1 Security challenges

According to Fiona et al. [23], the swarm robotic environment has its peculiar security challenges which include control, communication, physical capture and tampering and resource constraints. Fiona et al. [23] stated that swarms robots are prone to many risks that are out of control since robots in a swarm do not have a hierarchical structure with points of control. Such security threats, according to Fiona et al. [23] include loss of confidentiality or availability. Fiona et al. [23] further iterated that swarm robots communicate using technologies such as Radio-frequency (RF), infra-red (IR) technologies, haptics, audible sounding, audio and acoustic signalling in an underwater environment. Attackers can easily intercept these technologies. If the security of an individual robot is physically tampered with in a swarm, and such robot is reintroduced into the swarm, the behaviour of the swarm can change, and this can cause the other robots in the swarm to be harmed. This type of attack is unique to

swarm robotics technology. Fiona et al. [23] are also of the view that resource constraint such as inadequate storage, communication bandwidth, computational restrictions and energy are significant challenges confronting the security of swarm robots. Hence, the provision of security to an individual robot in a swarm is a challenge because a constraint on resources can restrict the types of security technologies deployed.

3.4.2 Limited local communication capabilities

Swarm robots do not have a global understanding of their environment and of the task that they are assigned to do. They only have a local perception of their environment. This lack of global knowledge can lead to a deadlock, thereby preventing the robots from progressing [52,53].

3.4.3 The stigma of widespread

Swarm robots are plagued with the stigma of widespread because their principles are rarely applied to real-life problems.

3.4.4 Lack of reliable communication

Swarm robots run on low power sources which support low transmitters. These transmitters have problems when transmitting and receiving instructions from the central control system. Hence, the mode of communication in swarm robots is hampered.

3.4.5 Uncertainty

This occurs when a robot is not aware of the intention of other robots in the swarm.

Consequently, the robots in the swarm compete rather than engaging in co-operation [23].

3.4.6 Interferences

Robots in a group can interfere with one another through collision or occlusion [23].

3.5 RQ5: What are the Swarm Robotic Platforms?

Several swarm robotic platforms have been developed in the past [54]. Typical examples of these platforms include kilobot, Collective Cognitive Robots (CoCoRo) and swarmbot. This section critically appraises swarm robotic systems and their potential applications.

3.5.1 Kilobot

Kilobot is a mobile robot that was developed by Radhika Nagpal and Michael Rubenstein at Harvard University in November 2010 [55]. The design of kilobot is inspired by social insects, particularly ants and bees. The goal of kilobot is to allow a user to program and experiment with collective behaviours in a large autonomous swarm. Kilobot usually operates in a group or swarm of dozens to a thousand (1024) unit. They are capable of communicating with one another with infrared transmitters and receivers and can execute complex self-organization as a swarm. They move with the aid of vibration motors. The kilobot swarm is cost-effective and scalable. They are typically used for corporate transportation, human-swarm interaction, and shape self-assembly. Fig. 6 shows the kilobot swarm.

Fig. 6. Kilobot swarm [52]

3.5.2 Collective cognitive robots (CoCoRo) swarm

The Collective Cognitive Robots (CoCoRo) swarm is an underwater swarm of robots that is funded by the European Union. The swarm is composed of forty-one autonomous agents that can learn from experience and their environment. Hence, they are cognitive, and a school of fishes inspires the CoCoRo swarm. Their primary goal involves monitoring, searching, maintaining, exploring and harvesting resources in underwater habitats while searching the habitat for hard to find targets such as black boxes of submerged planes, valuable resources or toxic waste dumps [56]. The CoCoRo swarm is as shown in Fig. 7.

3.5.3 Swambot

The swarmbot is a European IST-FET (Future and Emerging Technologies) project that consists of an autonomous, self-assembling and self-organizing robot colony that is made up of 30-35 small and mobile devices, called s-bots [58]. According to Nolfi et al. [59], each s-bot in the swarm has simple sensors and motors, limited computational capabilities, and physical links which allow it to connect to the other s-bots in the swarm. Swarm-bots are typically used for space exploration, search and rescue mission, and underwater exploration. Swarm-bots is as shown in Fig. 8.

3.5.4 Milybot

The Milybot, as shown in Fig. 9, is a robot swarm that is comprised of a set of eight agents that are autonomous in nature and exchange data amongst one another via wireless transmission [61]. According to Vega and Buscaron [62], Milybot is not self-reconfigurable and self-organized. Milybot lacks actuators and connection mechanism for physically attaching to other modules, and it is also expensive [62].
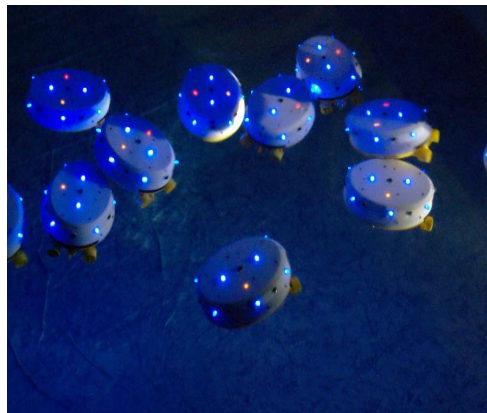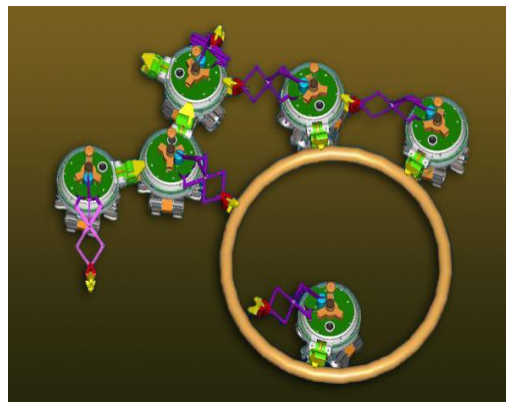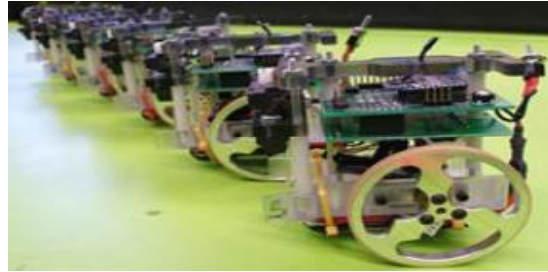

Fig. 7. CoCoRo swarm [57]

Fig. 8. Swarm-bot [60]

Fig. 9. Milybot [61]

3.5.5 Polybot

Polybot, as depicted in Fig 10, is a modular self-reconfigurable robot. Modularity provides versatility at several levels in collective robots [63]. Hence, polybot is very versatile, robust and cheap. Polybot cannot work in an unknown environment with a rough surface or when obstacle avoidance is a challenge [63]. Also, its sensory unit is inadequate for mapping of the environment [63].

3.5.6 Colias

Colias, as shown in Fig. 11, is an open-source, low-cost mobile robot inspired by honeybees. Colias uses BEECLUST aggregation to mimic the behaviour of young honeybees [65].

3.6 RQ6: How are Tasks Allocated among Swarm Robots?

Swarm robots perform quite some tasks, just like their counterparts in the natural swarm. For instance, weave ants join their bodies together so that they can float on water in order to escape the flood, ants can also pull a stick from the ground to build their nest. Swarm robots also engage in all these tasks. Fig. 12 shows ants and robots constructing their nests.

Robots can be classified based on the number of tasks that they can perform at a particular period. These robots include single-task robots and multi-task robots [69]. Single task robots perform one task at a time while multi-task robots perform multiple tasks at a time. Swarm robots are usually multi-task robots [69]. Individual robot in the swarm is assigned responsibilities or duties during the execution of a task. This process is referred to as task allocation. Specifically, task allocation can be defined as the process of assigning tasks to individuals in a team in order to maximize the performance of the system. Co-operation and teamwork are essential characteristics required for task allocation. Co-operation is required to make a task more efficient and robust. At the same time, collaboration among robots can also be used to speed up the execution of a task. Task allocation in robotics can either be intentional or self-organized [70].

Fig. 10. Polybot [64]
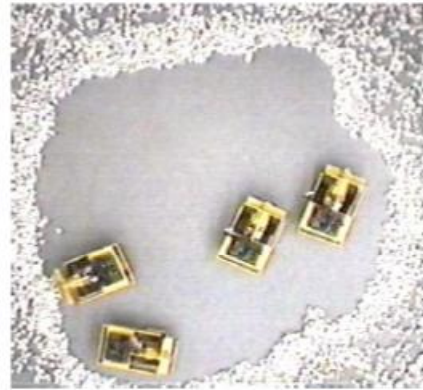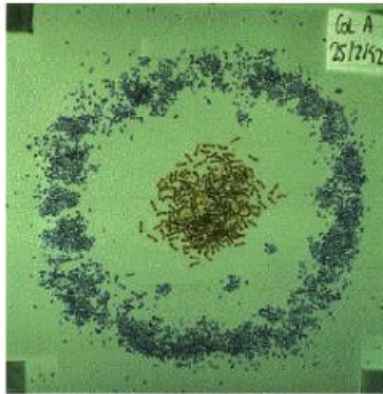
Fig. 11. Colias [66]

Fig. 12. Nest Construction by ants and robots [67,68]

In intentional task allocation, tasks are allocated based on negotiations. One of the methods used in intentional task allocation in swarm robotic systems is the market-based strategy. The market-based strategy for task allocation in swarm robots was designed by Dias et al. [71]. In this approach, an auctioneer announces tasks, and the robots make bids by indicating their cost to deal with the tasks [71]. The auctioneer decides which robot in the swarm will be assigned to a task based on the bidding made. The disadvantage of this approach is that the auctioneer serves as a central decision-maker which contradicts the decentralized and distributed nature of swarm robotic systems. The market-based strategy reduces the scalability and robustness of the system [72].

The self-organized based task allocation system derives its inspiration from the division of labour in social insects. An example of this task allocation system is the threshold-based strategy. The threshold-based method involves the assignment of different task thresholds which are sent out in the form of signals to swarm robots [73].

3.7 RQ7: What is the Interaction between Humans and Swarm Robots?

The interaction that exists between human-beings and swarm robots is known as Human Swarm Interaction. It is pertinent to note that there exists a significant difference between Human-Robot Interaction (HRI) and Human-Swarm Interaction (HSI). In HRI, the human interacts with a single social robot. In contrast, human operators interact with a large number of robots in HSI [20]. Besides, there is no social interaction between human beings and robot swarms in HSI. However, HSI is a sub-field of HRI [73]. HSI can be defined as the study of the interaction between human beings and robots in a swarm. Brambilla et al. [74] define HSI as the study of how humans interact with a swarm to control it and receive feedback from it. There are four types of HSI. These include intermittent interaction, environmental interaction, persistent and parameter setting interactions [75,76]. In intermittent interaction, the behaviour of a robot swarm is changed when a human operator influences the behaviour of a subset of the swarm. In environmental HSI, the human operator manipulates the swarm environment;

this in turns influences the individuals in the swarm to adapt to a given behaviour. The human operator provides a continuous control input for the swarm or the individual robot in the swarm in persistent HSI while in parameter HSI, the behaviour of a robot swarm is changed when an operator changes the parameters of the swarm such as the distance at which robots attract or repel each other.

One of the advantages of HSI, according to Debruyn [32] includes the ability of swarm of robots to assist human beings in moving in dangerous environments. The major challenge attributed to HSI is that most studies in swarm robotics are limited to virtual reality simulations in Computer Science [20]. Consequently, the principles of swarm robotics are rarely applied to real-life problems. Hence, it is difficult to understand how human beings interact with swarm robotic systems without a clear understanding of these systems in real life. Despite this challenge, Podevijn [20] identified five issues in HSI. These include robot swarm control, interaction interfaces, bandwidth limitation and neglect benevolence, level of automation, and formal verification.

3.7.1 Robot swarm control

In robot swarm control, the human controls a single robot or a subset of robots in order to influence the behaviour of the other robots in the robot swarm.

3.7.2 Interaction interfaces

In interaction interfaces, an interface is usually provided to allow human beings to interact with a robot swarm by issuing commands to and receiving feedback from the robot swarm. Examples of interaction interfaces in HSI include graphical user interfaces, gesture interfaces, face engagement interfaces, voice interfaces and haptic interfaces [75].

3.7.3 Bandwidth limitation

Bandwidth limitation exists when there is a communication constraint between the human and the robot swarm due to hardware limitations or limited power of communication radios [76].

3.7.4 Neglect benevolence

Neglect benevolence is a term used to describe a situation where a robot swarm is left to stabilize before issuing a new command [76]. This is because the command issued is dependent on the state of the swarm. Hence, in neglect benevolence, the human operator is not allowed to issue commands frequently to the robot swarm until it becomes steady. Conversely, Xu et al. [77] introduced the concept of neglect tolerance in HSI. Neglect tolerance is defined as a time a human operator can neglect a robot without degradation in the performance of the system [76]. In neglect tolerance, an individual robot is neglected because the performance of each individual robot decreases differently with time, hence the time it takes a human operator to service an individual robot in the swarm is reduced.

3.7.5 Level of automation

The level of automation is defined by Cummings [78] as the degree to which humans make decisions that are required by an autonomous system to function such as a computer or a robot.

3.8 RQ8: How is Information Exchanged among Robots in a Swarm?

In natural swarms, communication can either be direct or indirect. For direct communication, social insects and animals use voice, gestures or tentacles for information exchange. In contrast, in indirect communication, the individuals' sense and react to the information in the environment. They also give feedback to the environment. A typical example of an indirect mode of communication in robot swarm is the use of pheromone or secretions to indicate the presence of danger or the path of food sources [79].

According to Cao [80], information exchange in swarm robots can be direct or explicit communication and indirect or implicit communication. There are two types of direct communication. These include peer-to-peer and broadcast. In peer-to-peer communication, the individual robots in the swarm share information directly without the need for a central system or robot while in broadcast communication, the message is taken from an individual robot and transmitted to all the individuals in the swarm. Direct communication is usually achieved using local communication via wireless transmission such as infrared and radiofrequency. In indirect communication, the environment serves as the interface for the interaction of the robot. The indirect communication in swarm robots is similar

to the communication found in natural swarms. An individual robot leaves virtual pheromones in the environment for other robots to sense. This implicit model of communication is also referred to as stigmergic communication. Figs. 13 and 14 illustrate the peer-to-peer and broadcast communication modes of communication in a swarm robot.

Higgins et al. are of the view that implicit or explicit communication method can be jammed, intercepted or otherwise disturbed relatively easily by an attacker [80]. Hence, the need for security measures during information exchange in swarm robotics. Typical examples of security measures used during information exchange in swarm robots include identity and authentication, intrusion detection and critical management. In identity and authentication, a swarm determines if it is interacting with a legitimate entity or not. In intrusion detection, a swarm detects if a foreign entity joins it either maliciously or accidentally and ultimately removes it from the swarm. Key management requires the use of cryptographic keys to define which groups of robots can apply security services [80].

4. SUMMARY OF THE RESULTS OF THE RESEARCH QUESTIONS

The result of the first research question shows that swarm robots are robust, scalable, exhibit cooperative behavior and the interaction between individuals in the swarm is local and not global. The second research question reveals that swarm robots exhibit certain properties which include aggregation, flocking, foraging, dispersion, self-wandering and self-organization. The third research question reveals that swarm robotics systems are useful for real life applications such as medicine, environmental exploration, oil spill cleaning, surveillance, search and rescue mission, demining, agriculture and construction. The fourth research question also reveals that swarm robots are plagued with diverse challenges which include communication challenges, security challenges as well as the stigma of widespread. The fifth research question unveils that kilobot, Collective Cognitive Robots (CoCoRo) and swarmbots are typical examples of swarm robotic platforms. The sixth research question shows that swarm robots perform tasks, and tasks are usually allocated to individual robots using two methods which include the intentional based method and the self-organized method. The seventh research question reveals that human beings and swarm robots can interact and this interaction is known as Human Swarm Interaction. The last question unveils that information is exchanged amongst individual robots in a swarm and that information is exchanged in the swarm by direct or explicit communication and indirect or implicit communication.
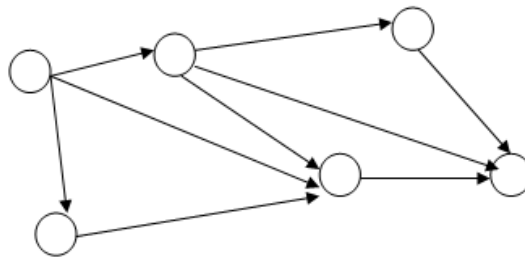

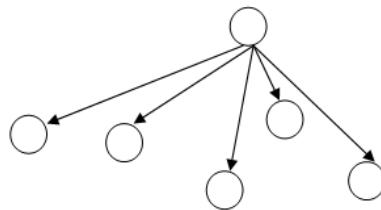**Fig. 13. Peer-to-peer communication in swarm robot**

Fig. 14. Broadcast communication in swarm robot

5. STRENGTHS AND LIMITATIONS OF THE STUDY

This study provides a systematic review of swarm robots. The study identified different types of swarm robots platforms and the types of properties that are exhibited by swarm robots. The study also examined the benefits and challenges of swarm robots. Contemporary issues such as task allocation, human-swarm interaction and information exchange in swarm robots were discussed in this study. However, this study is limited to studies that were published in the English Language. Hence, relevant studies published in other languages relating to swarm robots were exempted from this study.

6. CONCLUSION

This study systematically reviews swarm robots because studies in swarm robotics are usually applied to virtual reality simulations. The study adopted the 5-step approach proposed by Khan et al. Eight research questions were formulated in order to understand and summarize the empirical proofs of the state-of-the-art studies on swarm robots. In order to answer these questions, eighty literatures comprising of journal articles, technical reports, books, and conference proceedings in swarm robots were reviewed. The result of the review shows that swarm robots are robust, scalable, exhibit cooperative behavior and the interaction between individuals in the swarm is local and not global. The study also reveals that swarm robots exhibit certain properties which include aggregation, flocking, foraging, dispersion, self-wandering and self-organization. It can also be deduced from the study that swarm robotics systems can be applied to diverse fields which include medicine, environmental exploration, oil spill cleaning, surveillance, search and rescue mission, demining, agriculture and construction. The study reveals that robots are plagued with diverse challenges such as communication challenges, security challenges as well as the stigma of widespread. The study reveals that tasks are allotted to individual robots in a swarm robotic system using two methods which include the intentional based method and the self-organized method. The study also reveals that human beings and swarm robots interact through a process known as Human Swarm Interaction.

7. DIRECTIONS FOR FUTURE RESEARCH

This research systematically reviews diverse issues in swarm robotics such as applications and challenges of swarm robots, task allocation in swarm robots and human-swarm interaction. This was with a view of giving a better understanding of the research field. However, the study did not consider the role of physical interactions in swarm robotic systems which are often underestimated. Hence, it can be put into consideration in future studies. In addition, topics such as collective decision making, fault tolerant properties and the methods of developing of low cost swarm robotic platforms that can be applied to real life situations should be considered in the future.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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