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Swarm robotics reviewed

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SUMMARY
We present a review of recent activities in swarm robotic research, and analyse existing literature in the field to determine how to get closer to a practical swarm robotic system for real world applications. We begin with a discussion of the importance of swarm robotics by illustrating the wide applicability of robot swarms in various tasks. Then a brief overview of various robotic devices that can be incorporated into swarm robotic systems is presented. We identify and describe the challenges that should be resolved when designing swarm robotic systems for real world applications. Finally, we provide a summary of a series of issues that should be addressed to overcome these challenges, and propose directions for future swarm robotic research based on our extensive analysis of the reviewed literature.

KEYWORDS: State-of-the-art; Swarm; Robotics; Review.

1. Introduction

Swarm robotic (SR) research has recently emerged from the application of swarm intelligence concepts into multi-robot systems, which focuses on physical embodiment and realistic interactions among the individuals themselves and also between the individuals and the environment.[1] The term "swarm" refers to a large group of locally interacting individuals with common goals. It is used to describe all types of collective behaviours even though it brings up associations to joint movement in space.[2] Swarm intelligence is the collective intelligence that emerges from interactions among large groups of autonomous individuals.[3,4] This term was first used by Beni and Wang[5] to describe a particular type of cellular robotic system. Some of the earliest works on swarm robotics are by Walter, Wiener and Shannon in the mid-1940s. They investigated the social behaviour that emerged from the interactions of structurally simple turtle like robots with touch and light sensors.[6,7] Since then, a wide range of SR systems have been studied; readers may refer to the following seminal research work on flying robots,[8–10] ground moving robots,[11–14] and robots that operate in water.[15,16]

Swarm robotic research is often inspired from biological systems such as insect colonies,[9,17,18] flocks of birds,[19,20] schools of fish,[2,21,22] groups of amoeba,[23] bacteria colonies,[24–26] and cells in human or animal bodies.[1,27] Inspiration is taken from nature because studies into natural systems have shown to support development of novel rule sets that can be used to solve difficult problems that might be impossible to solve with traditional techniques.[18,28] An additional benefit is that one can investigate, test and update new theories by comparing them directly to the source of inspiration.[29]

1.1. Motivation for conducting swarm robotic research

A range of potential advantages associated with the use of appropriately controlled robot swarms is the main motivation for SR research. Robot swarms can do the following:

- Robot swarms make it possible to exploit the sensing capabilities of large groups, which means that one can find areas of interest quickly, decide whether to enter them and quickly determine when to leave.[21,30,31]
- They support superior situational awareness.[32]
- They support higher level of robustness towards mission failure than systems that rely on one individual, as other individuals can take over work previously conducted by a lost or failed member of the swarm[26,31,33,34]
- They distribute workload among its members to achieve more significant results such as conducting tasks over large spatial areas,[35] manipulating the environment more efficiently than one individual[36] or attacking from multiple directions at the same time.[32]
- They carry out a large number of tasks simultaneously with simpler and cheaper robots than if more sophisticated robots were used to conduct each task individually.[35]

Swarm robotics can also draw from the advantages associated with general robotics and therefore support situational awareness in potentially hazardous environments without exposing humans to danger.[36]

However, it should be noted that there also are some drawbacks associated with SR systems. One of these is that neither centralized nor decentralized communication and control schemes make it easy for a human operator to control SR systems. The problem with centralized SR systems is that the underlying communication and control schemes do not scale well with increasing numbers of individuals and they are sensitive to loss of central leaders.[37–39] As a result, pure centralized systems do not support a robust control of large swarms by a single human operator.

Decentralized SR systems, on the other hand, are unable to synthesize or access global data unless all individuals are connected to each other, as no central mechanism that can synthesize data from all members of the swarm exists. It is not desirable to assume that all individuals connected as high

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connectivity in practice easily paralyse large swarms. It is therefore hard to generate global data that can be used to facilitate globally optimal control by a human operator when decentralized SR systems are employed. It is also difficult for a human controller to predict the exact behaviour of these systems, as the global behaviour emerges from the interactions among numerous locally interacting individuals.

Even with the drawbacks of SR systems the potential benefits are highly sought after in a wide range of application areas, including nuclear, chemical and biological attack detection,[40] battlefield surveillance,[31] space exploration,[28,37] pollution detection[41–44] and search and rescue.[20,45–47] Swarm robotic research can therefore have a significant economical and social impact.

In the following sections we review a wide range of seminal SR studies published in the last 30 years in order to (i) provide an overview of various robots that can be incorporated into SR systems, and (ii) draw out a series of issues that should be addressed in order to get closer to a practical SR system for real world applications. The focus is set on software issues, as the scope of this paper would be too wide if hardware issues were to be addressed. We also provide an update of earlier reviews.[1,4,34,35,48–57] In addition, we draw on experiences from work conducted on multi-robot systems and self-organizing sensors, as valuable lessons relevant to swarm robotic can be obtained from these closely related fields. In the end of the paper we provide a graphical overview of formation of shapes that have been generated by SR systems to date along with the methods that have been used to generate them.

This SR review is required, as earlier reviews do not offer insight into how we can get closer to a practical SR system for real world applications. Another reason is that earlier reviews do not provide a comprehensive graphical overview of formation of shapes that have been generated by SR systems to date along with the methods that have been used to generate them.

2. Robots in Swarm Robotic Systems

This section describes various styles of robots that can be incorporated into SR systems to give readers a general overview of different hardware options that are available when devising SR systems for real world applications. We commence with a discussion on heterogeneous and homogenous robot swarms.

2.1. Heterogeneous versus homogenous swarms of robots

One of the first issues to address when designing an SR system should be to determine if the swarm should consist of heterogeneous or homogenous robots, as this will greatly affect how the underlying control schemes will operate.

Heterogeneous SR systems consist of robots with different designs or functionalities that usually complement each other in order to complete tasks efficiently. An example is the SR system that makes use of airborne robots to search for tasks on the ground from elevated positions, and wheeled robots to address the tasks that are found.[9,58] Another example is described in ref. [59], where a large mother ship and Micro Air Vehicles (MAVs) collaborate in scouting operations. The mother ship transports the MAVs to locations of interest and enables the overall SR system to (i) move to areas far away from its base station, (ii) carry technologies that make it possible to communicate over large distances and (iii) process large amounts of information. The MAVs, on the other hand, enable the SR system to spread out into environments of interest to collect data in an agile and efficient manner.[59] In both these examples the heterogeneous nature of the SR system supports efficient goal-directed behaviour. However, a drawback with heterogeneity is that it becomes harder for robots to model other (potentially failed) robots in the swarm, which in turn reduces the SR system's robustness towards the failure of individual robots.[1,35] Most SR researchers therefore believe that heterogeneity should be avoided. As a result, nearly all SR research is conducted on homogenous robots, meaning that the robots have the same design and functionalities. Robots that have been used in homogenous SR systems include Swarm-robots,[14,53,60] Khepera[61] and E-puck robots.[62]

2.2. Self-assembling and self-reconfigurable swarms of robots

Swarm robotic literature has recently given a lot of attention to self-assembling and self-reconfigurable robots. Self-assembling robots differ from other classes of robots through their ability to connect to each other to form different connected patterns such as lines, rectangles, stars or arrows.[63] These robots are able to perform tasks that are impossible to accomplish with other classes of robots, including (i) moving over terrain that is so rough that individual robots are unable to traverse,[64] (ii) overcoming obstacles that are larger than individual robots,[14] or (iii) transporting objects that are too heavy for a single robot to carry.[65] Techniques that can be used to generate connected patterns autonomously are described in ref. [66].

Self-reconfigurable robots, on the other hand, can change their shape by modifying the connections to parts of their structure. This enables them to recover from damage, perform new tasks and adapt to new requirements.[4] These SR systems are commonly classified on the basis of their geometric structures.[67] Common structures include lattices with regular three-dimensional (3D) patterns such as hexagonal grids or cubes,[68,69] chains connected in strings and tree topologies.[70,71]

In the following section a series of challenges that must be addressed when designing software for practical SR systems is described. Issues that should be addressed to overcome these challenges are also drawn from a careful examination of relevant literature. We focus on software issues for homogenous SR systems that do not self-assemble or self-reconfigure, as these systems currently are the most common ones.

3. Challenges When Designing Software for a Swarm of Robots

When attempting to design practical SR systems for real world applications, one is faced with a wide range of software challenges. Challenges that are highlighted in seminal literature include the following:

(1) Selecting appropriate centralized or decentralized communication and control schemes.
(2) Incorporating important behaviours and traits such as self-organization, scalability and robustness.
(3) Devising mechanisms that support goal-directed formations, control and connectivity.
(4) Implementing mapping, localization, path planning, obstacle avoidance, object transport and object manipulation functions that enable swarms of robots to interact efficiently with the environment.
(5) Addressing problems related to energy consumption.

In this section, we review the work that enables us to draw out a series of issues that should be addressed to overcome these challenges. We commence by drawing out issues that are relevant to selection of appropriate communication and control schemes.

3.1. Centralized versus decentralized communication and control schemes

The choice of either a centralized or a decentralized control and communication scheme is one of the most fundamental issues to be addressed when designing an SR system.[35] Both schemes have contributed independently to the field of swarm robotics, and both have produced valuable results.[4]

Centralized systems interact with central planners, which collect and synthesize data from individual robots and specify how the swarm should operate on a global level. There are several benefits associated with the use of centralized systems. One benefit is that information from members of the swarm can be synthesized and analyzed so that the behaviour of the swarm can be planned according to "complete" prior knowledge.[72] Centralized systems can also offer direct control of each individual and therefore make it easy to predict the behaviour of the overall system. However, there are also some significant problems related to the use of centralized SR systems. Two of the most significant problems are that (i) the underlying communication and control schemes do not scale well with the increasing number of individuals, and (ii) such systems are sensitive to the loss of central "commanders."[37–39,73] Also, individuals located close to the central "base" are often depleted for energy before other individuals, as they are commonly used to carry information back to the "base" and therefore must transmit more data than individuals located further away.[37] As a result, the entire swarm can become disconnected from the "base."

Decentralized systems use distributed communication and control mechanisms. The decentralized paradigm is commonly preferred in swarm robotics because of the following reasons:

(1) It reduces delays and impracticalities associated with centralized processing.[74]
(2) The computational complexity of decentralized systems can be made independent from the number of individuals in the network.[35,39,75]
(3) It reduces sensitivity to loss of particular individuals, such as leaders.[1,39,74,76]
(4) It naturally exploits parallelism.[35]

A drawback with decentralized systems is their inability to support global synthesis of sensory information collected by the swarm, and decisions therefore cannot be taken on the basis of "complete" global knowledge.[38,39,73] This is a significant drawback for the applications where a human controller requires access to high-level information such as generated maps or target locations. Another impediment is the difficulty to predict the behaviour of decentralized systems, as their behaviour emerges from numerous local interactions rather than direct specifications. Furthermore, the lack of global knowledge and supervision can further lead to oscillatory behaviour, meaning that individuals move repeatedly back and forth.[37] This is a significant problem as it increases energy wastage.

Graph theory is widely used as a theoretical basis for establishing communication and control structures in decentralized SR systems, as this makes it possible to abstract away the complex sensing and communication characteristics of individual robots so that research efforts can focus on the underlying interaction topologies that lead to desired global behaviours.[21,74,77–80] Consensus algorithms are often used to enable individual units in SR systems to reach a common perspective of objectives and state of the world so that they can agree on the direction of movement, where to meet or the location of intruders.[22,81,82] Consensus algorithms have proved to work well in combination with graph theory.[81] Another tool that is often employed in decentralized SR systems is the Voronoi diagram.[20,33,43,76] This diagram can be used to determine the spatial relationships between individuals (e.g. if two individuals are neighbours) and has assisted in solving both the area coverage problem and the rendezvous problem.[20]

Not all systems are strictly centralized or decentralized,[35,83] and research has revealed that it is desirable to find a proper balance between the two paradigms.[38] Such a balance might be reached by exploiting the characteristics of decentralized swarms, while at the same time incorporating functions, which allow a central controller to conduct high-level supervision of the systems through leader election,[84] command of a leader[22,85,86] or command of several leaders.[87] Such hybrid systems give the central controller the ability to guide the overall behaviour of the swarm, and at the same time reduces the complexity associated with the centralized command as each individual in the swarm only interacts with its local neighbours.[88] Hybrid systems might therefore be used to overcome the difficulties associated with "pure" centralized or decentralized systems. This conclusion was also reached in refs. [38, and 73].

An analysis of literature relevant to the challenge of formulating a communication and control scheme for SR systems is presented in Table I. One can observe that centralized and decentralized schemes overcome each other's shortcomings and a solution may therefore be to devise hybrid-distributed schemes.

3.2. Important behaviours and traits

Work that describes the design of behaviours and traits that practical SR systems for real world applications are expected

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Table I. Formulating a communication and control scheme.

Formulating the communication and control scheme	
Analysis	
Strengths associated with centralized schemes • Behaviours can be planned according to "complete" prior knowledge.[72,73]	Strengths associated with decentralized schemes • Reduces delays and impracticalities associated with centralized processing.[74] • Computational complexity is independent of the number of individuals.[35,39,75] • Reduces sensitivity to the loss of particular "leader" individuals.[1,39,74,76] • Naturally exploits parallelism.[35]
Drawbacks associated with centralized schemes • Computational complexity increases with the number of individuals in the swarm.[37–39] • Sensitive to loss of central "commanders."[37–39] • Individuals located close to a central "base" are often depleted of energy before other individuals.[37]	Drawbacks associated with decentralized schemes • Does not support synthesis of information collected by all individuals, and decisions can therefore not be taken on the basis of "complete" global knowledge.[38,39,73]
Conclusion Centralized and decentralized schemes overcome each other's shortcomings, and the solution therefore appears to be in devising a hybrid distributed system that overcomes the drawbacks of both individual schemes.	

to demonstrate are reviewed in this section. We commence by reviewing the work on self-organization.

3.2.1. Self-organization. Self-organization is a process that allows global patterns to emerge from low-level interactions.[23,89–93] Literature suggests that self-organization should be exploited in swarm robotics as it enables the swarm to autonomously adapt to changing conditions by modifying its structural organization so that it can distribute itself optimally for a given task, or update its topology automatically when individuals are added or removed.[17,31,35] One can therefore reduce difficulties associated with coordinating large groups of individuals by exploiting self-organization as the system is given the ability to monitor and modify its behaviour without external intervention.[17,94] This is obviously valuable in swarm robotics as these systems naturally consist of large numbers of individuals and coordinating all of them externally therefore could be an overwhelming task.[95] A drawback with the use of self-organization in swarm robotics is that it is hard to predict the behaviours of a self-organizing swarm.[9] It is therefore beneficial to investigate how a self-organizing swarm can be supervised on an abstract level if one wishes to ensure that the system accomplishes a series of high-level goals in an orderly fashion. An analysis of literature relevant to the challenge of formulating self-organizing behaviours for SR systems is provided in Table II.

One can observe that self-organization allows swarms to adapt autonomously to the environment and reduces difficulties associated with controlling large groups of individuals. On the other hand, however, it can be hard to predict the behaviour of self-organizing systems. One can therefore conclude that one should aim to devise a self-organizing SR system that can be supervised on an abstract level so that one can reap the benefits of self-organization, and at the same time ensure that a series of high-level goals can be accomplished in a controlled manner. How traits such

Table II. Formulating self-organizing behaviours.

Formulating self-organizing behaviours	
Analysis	
Strengths associated with self-organization • Enables swarms to autonomously adapt to changing conditions.[17,31,35] • Reduces difficulties associated with coordinating large groups of individuals.[17,94]	Drawbacks associated with self-organization • It can be hard to predict the behaviours of self-organizing systems.[9]
Conclusion Devise a self-organizing SR system that can be supervised on an abstract level.	

as scalability and robustness can be promoted in SR systems is discussed in the following section.

3.2.2. Scalability and robustness. Swarm robotic systems must be scalable and robust to operate efficiently in dynamic and unpredictable real world environments. To be scalable, an SR system should be able to operate under a group size ranging from a small number to several thousand individuals or more.[1,34] A common way of supporting scalable system design involves employing decentralized communication and control strategies.[35,76] A recent scalable SR mechanism is the morphogenesis-based technique that has been used to generate formations and enable self-reconfigurable robots to adapt their shapes to environmental constraints.[96] Other examples include the potential fields based on SR systems that (i) enable groups of robots to generate formations while avoiding local minimums,[97] (ii) distribute evenly across obstacle-filled environments[44] and (iii) generate and maintain formations while preserving connectivity.[98]

The term "robustness" refers to the ability to continue to operate correctly in the face of interferences such as the failure of individual robots.[99] It is important to ensure

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Table III. Making SR systems scalable and robust.

Ensuring that the system is scalable and robust	
Analysis	
Strengths associated with scalable systems	Drawbacks associated with scalable systems
• Systems can operate efficiently under varying group sizes.[1,34]	–
Strengths associated with robust systems	Drawbacks associated with robust systems
• Systems can operate in the face of interference and loss of individual robots.[99]	–
Conclusion	
Take measures to ensure that mechanisms used in the SR system are	
(i) scalable by employing decentralized communication and control strategies;	
(ii) robust by exploiting the redundancy inherent in swarms, ensuring that the system is scalable and uses simple individuals.	

that SR systems are robust to increase the likelihood of accomplishing mission goals in the face of environmental changes, loss of individuals or changes in mission plans. Robustness is particularly important in application areas where one expects environmental factors to change abruptly, or it is likely that individual robots are destroyed.[32,79] A series of measures can be taken to support robustness. One can, for example, include redundant system components, ensure that the system is scalable, use simple individuals, as they are less prone to failures than more complex individuals, and include decentralized schemes.[1,10,44,74]

An analysis of literature relevant to the challenge of facilitating scalability and robustness in SR systems is provided in Table III. No drawbacks associated with incorporating these traits were uncovered, but one possible drawback is increased implementation time. Nevertheless, the analysis shows that there are great benefits associated with incorporating these traits into SR systems and one should therefore take measures to support scalability and robustness when designing an SR system.

3.3. *Formations, control and connectivity*

History has shown that the success of swarming often depends on the ability to generate and maintain appropriate formations. For example, losing a rear guard can result in a whole group being annihilated, encirclement of an enemy target can lead to quick victory, and a swarm in a dispersed formation has a greater chance of surviving heavy attacks than a swarm in a compact formation.[32] It is therefore important to ensure that appropriate formations can be generated when SR systems are to be employed into real world domains.

Different distribution patterns have been used to achieve desired formation shapes in swarm robotics. However, equilateral triangle patterns are optimal in terms of the number of individuals needed to cover an area.[37,100] This pattern should therefore be used if the aim is to support all-embracing situational awareness with a limited number of individuals. (Refer to Appendix 1 for a graphical overview of the reviewed formation patterns and methods that have been used to generate them.) Alternative shapes, which have been generated using graph theory, are referred to as k3, k5, bilateration, wheel, c2, c3, bipartite, rectangular and straight line.[21,74,101,102] Operations that can be used to modify these "graph"-based formations, such as vertex addition, edge splitting, formation splitting and formation merging along with relevant concepts such as rigidity and structural persistence, are discussed in refs. [77, 80].

Graph theory is not the only option that can be used to generate formations. Different formation shapes, such as lines, rectangles, stars and arrows, can also be grown from a seed robot using simple rule sets as shown in ref. [63], while circular, ring, R-shaped, N-shaped and lobed formations can be produced through the use of morphogen gradients.[103–105] Voronoi diagrams can also be used to generate formations, and have been used to form segments, polygons, ellipses and uniform distributions.[33] Potential fields have been used to generate elliptical, triangular, parallelogram and five-pointed star formations.[106–108] Vortex formations, on the other hand, have been generated with passive mechanism based on inelastic collisions among agents as shown in ref. [109].

To enable a formation to move as a cohesive unit, a number of issues must be addressed. At the highest level, the trajectory of the formation must be defined according to available terrain information or particular task requirements. The resulting path can be followed by one or more leaders[85] or by the centre of gravity of the formation.[21] At an intermediate level, functions that enable individuals to maintain their desired shape variables and allow for modification of the formation shape must be included. To maintain the desired shape variables, one must ensure that the individuals can synchronize their direction of movement, speed, acceleration and angular velocity.[21] These synchronisation behaviours can be realized through the use of consensus algorithms,[81,82] or by enforcing constraints on relative distances and rotations. Graph theory offers tools that can be used to define appropriate constraints.[80] An example that makes use of graph theory to maintain stability in leader follower type SR systems is presented in ref. [110], while a method that can be used to perform stability analysis of swarms in 2D space is accessible from ref. [111]. Functions that allow for transitions between different formation shapes should be included at the lowest level[85] and transition matrices[81] are often used to model these transitions.

To march as a cohesive unit, individuals in a formation must be connected, meaning that they must be able to share information. In other words, the sensing range of the individuals must overlap.[112] Connectivity is essential in swarming, as disconnected parts of a swarm are unable to interact with the remaining individuals, which in turn makes the disconnected individuals useless.[27,100] Connectivity can be reached by (i) deploying a large number of individuals, (ii) modifying the topology of the swarm, (iii) using specialized individuals with long-range communication capabilities or (iv) using individuals with enhanced mobility that can transport data between isolated parts of the swarm.[113] A range of studies explore how

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Table IV. Generating and maintaining connected formations.

Supporting formation generation, control and connectivity	
Analysis	
Why generate formations?	Drawbacks associated with using formations
• Success of swarming often depends on the ability to generate and stay in appropriate formations.[32]	• Individuals must be connected to share information.[112]
• Certain formation distributions address particular problems more efficiently than others.[37,100]	• Energy consumption is affected by the method that is used to generate and maintain connectivity.[118]
Conclusion	
Take measures to ensure that (i) generated formations efficiently support the task at hand; (ii) the method used to establish and maintain connectivity is energy-efficient.	

connectivity can be reached and maintained. One such study investigates that how efficiently hexagon, rhombus, square and triangular deployment patterns facilitate both connectivity and coverage.[100] This particular study also describes a strip-based deployment scheme that can be used to achieve 2-connectivity, meaning that two connection lines run through the network of robots so that the robots are still connected even if one line of robots is broken. Other studies have investigated how connectivity can be reached and maintained through the use of neighbour or proximity graphs.[114] The criteria for establishing a connection between two robots have traditionally been based on only physical distance.[115,116] However, recently a more precise model has been proposed.[117] This new model improves on previous works by taking into account both distance constraints and obstacles that block the line of sight between robots when determining if a connection link can be generated or maintained. This latter study also tackles the problem of navigating swarms through environments with obstacles while maintaining specified connection links. One important issue to keep in mind when selecting a technique that should be used to generate and maintain connectivity is the amount of energy that is spent on these processes depends on the technique that is employed and the amount of data that must be transferred between the robots to preserve connectivity.[118] One should therefore, select the most energy-efficient method that satisfies the constraints of the intended application area.

An analysis of literature relevant to the challenge of generating and maintaining formations is presented in Table IV. One can observe that the chance of completing tasks successfully with swarms often depends on the ability to generate and maintain appropriate formations. However, to enable SR systems to operate as cohesive units, the individuals in the swarm must be connected. Since energy consumption is affected by the method that is used to enable connectivity, one should carefully select the most energy-efficient method that supports the task at hand.

3.4. Functions that enable swarms of robots to interact with the environment

Literature relevant to the challenges associated with generating functions that enable swarms of robots to interact with the environment is reviewed in this section. We focus on (i) mapping and localization, (ii) path planning and obstacle avoidance and (iii) object transport and manipulation. Literature that tackles issues relevant to mapping and localization is reviewed first.

3.4.1. Mapping and localization. Mapping and localization should be conducted if one wants to support efficient goal-directed performance with an SR system without having to introduce additional nodes that can facilitate navigation between points of interest.

Mapping can be defined as the process of generating a representation of physical environment by transforming sensory data into spatial models.[119] There are two types of maps – topological and geometric that can be generated in the mapping process. Topological maps consist of abstract representations of the environment and use simple points and lines to represent places and movements. Geometric maps, on the other hand, include detailed representations of the environment. Topological maps are discussed in greater detail in refs. [120, 121], and geometric maps are described to a greater extent in ref. [4]. Mapping can potentially be conducted efficiently by swarms, as the members of the swarm can collaborate in the mapping process.[122] However, a difficulty associated with conducting mapping processes with "pure" SR systems is that these systems usually are highly decentralized, which makes it hard to synthesize and access global maps, unless some centralized mechanisms are also integrated into the system.[38,39] The problem can be addressed by introducing additional passive nodes such as GNATs, which support goal-directed navigation in a decentralized manner without the use of mapping or localization.[123] However, a drawback with this approach is that the swarm will be unable to operate without these additional nodes, which in turn decreases its flexibility.

Localization is the process of determining the positions of robots or targets in models of the environment and aids in the navigation of both individual robots and whole swarms.[4] A recent vision-based self-localization technique that can be used by individual robots in SR systems is described in ref. [124]. This particular technique makes use of data from a compass mounted on each robot, pre-captured images of the environment and image-matching methods to determine the location of each robot locally. Techniques that allow SR systems to locate targets in a decentralized manner include the particle swarm optimization (PSO)-based techniques that are presented in refs. [26, 125]. The only assumption is the presence of a non-linear emission that fades with the distance to the target. An additional target localization technique makes use of motor schema paradigms, neural networks and simple handwritten commands to enable decentralized SR systems to locate prey and bring them back to a nest.[126]

An analysis of the literature that was reviewed in this section is presented in Table V. One can observe that it is valuable to incorporate mapping and localization functions into SR systems. However, one can also observe that there

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Table V. Facilitating mapping and localization.

Facilitating mapping and localization	
Analysis	
Benefits associated with facilitating mapping and localization	Drawbacks associated with facilitating mapping and localization
• Mapping can potentially be conducted efficiently by swarms as several individuals can collaborate in the mapping process.[122] • Localization aids in determining the location of robots and targets in models of the environment[4] and therefore assists in the navigation of both individual robots and whole swarms of robots.	• Centralized mechanisms must be used to synthesise and access global maps with SR systems[38,39] unless additional inflexible nodes that can facilitate navigation between points of interest are introduced.
Conclusion	
Any robot should be able to facilitate the centralized mechanisms that are necessary for conducting flexible mapping and localization tasks to ensure that the SR system is robust towards failure of any one individual.	

are some drawbacks associated with incorporating such functions. To reduce these drawbacks one should make sure that the mechanisms, which are used to enable SR systems to conduct mapping and localization tasks, can be facilitated by any robot so that the swarm is robust towards the failure of any one individual.

Literature relevant to generating functions that enable swarms of robots to plan their movement and avoid obstacles is reviewed in the following section.

3.4.2. Path planning and obstacle avoidance. Path planning is necessary in order to navigate robots efficiently between specific locations in the environment.[127] Path planning mechanisms can either be local or global. Local path planning uses information from sensors mounted on the robots to navigate robots through unknown environments.[128] A range of techniques can be used to conduct local path planning with SR systems. A common technique is the PSO-style approach that enables robots to escape local minima and avoid obstacles while searching for paths towards goal destinations in 2D space.[129] A second method that is frequently used for local path planning in SR systems is the Ant-Colony Optimization technique, which enables groups of individuals to identify the shortest path between points of interest through the use of pheromone-inspired functions.[72] K-Bug, a less frequently used but effective local path planning technique, navigates robots towards goal points in a straight line and counters any obstacle encountered along the way by moving to the closest visible point on the obstacle until the robot can continue to move in a straight line towards the goal. Another uncommon but effective local path planning technique is referred to as D^*. This particular technique makes use of a support vector machine to support adaptive path planning and obstacle avoidance in unknown and dynamic environments.[130] The parameters of this technique are optimized with genetic algorithms.

In contrast, global path planning mechanisms use precise prior knowledge about the environment in the planning process.[72] In these situations path planning can be performed using classical single-robot path planning systems.[35] Regardless of what technique one selects, one should ensure that the planning process is not dependent on one particular specialized leader, as this would reduce the robustness of the system.

Obstacle avoidance is another fundamental issue,[127] and must be addressed to ensure that collisions are prevented. Basic obstacle avoidance techniques address static environments,[72,131] while more sophisticated techniques deal with dynamic environments with both stationary and moving obstacles.[130,132] One of the most basic obstacle avoidance techniques makes robots approaching an obstacle turn a random angle and move forward.[26,34] However, this approach does not ensure efficient goal-directed behaviour. A more sophisticated technique uses the Minkowski Sum diagrams and maze search strategies to define areas referred to as "collision fronts" around both stationary and moving obstacles. To avoid collisions, the robots are not allowed to move into these "collision fronts."[39] A different technique that also addresses both stationary and moving obstacles pushes individuals away from each other and distributes virtual nodes around stationary obstacles.[37] The movement of individual robots is then calculated by combining the pushing effect generated by both the neighbouring robots and the virtual nodes. Potential field theory can also be used to push individuals away from obstacles and other robots.[44] A technique that is fundamentally different to the ones described here employs neural controllers to enable individuals in swarms to learn how to avoid obstacles.[14] A potential drawback with all these techniques is that these do not by themselves ensure that the swarm as a whole regains its previous shape after moving through areas with obstacles. However, such techniques are presented in refs. [85, 133] and these latter techniques can therefore be used if an SR system must avoid obstacles while retaining a particular shape throughout a mission.

Literature that is relevant to devising functions that facilitate path planning and obstacle avoidance in SR systems is analysed in Table VI. One can observe that path planning and obstacle avoidance enables swarms and individual robots to navigate efficiently between specific locations without experiencing collisions. It is therefore important to incorporate these functions into SR systems to support goal-directed behaviour and avoid unnecessary damages or delays resulting from collisions. One should, however, be aware that the functions must not depend on one particular specialised

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Table VI. Incorporating path planning and obstacle avoidance functions.

Facilitating path planning and obstacle avoidance	
Analysis	
Benefits associated with facilitating path planning and obstacle avoidance	Important considerations associated with path planning and obstacle avoidance functions
• Enables swarms and individual robots to move efficiently between specific locations without experiencing collisions.[127]	• If these functions depend on one particular leader, then the system is prone to failure.[37–39]
Conclusion	
Use path planning and obstacle avoidance functions that do not depend on a specialized leader.	

Table VII. Incorporating object transport and manipulation functions.

Facilitating object transport and manipulation	
Analysis	
Benefits associated with facilitating object transport and manipulation	Important considerations when facilitating object transport and manipulation
• Large groups can perform tasks more effectively than individual entities.[36]	• Different types of transportation and manipulation functions (pushing, grasping and caging) have their own strengths and weaknesses.[4]
Conclusion	
Devise mechanisms that enable SR systems to manipulate and transport objects efficiently in the application area at hand.	

leader as this makes the system prone to failure if the leader breaks down or goes missing.[37–39] If a leader–follower paradigm is to be used, then the leader should be easily substituted with one of the followers.

Literature relevant to addressing the challenge of formulating functions that enable swarms of robots to transport and manipulate objects is reviewed in next section.

3.4.3. Object transport and manipulation. Research into the use of swarms for transport and manipulation tasks can have a significant economical and social impact, as large groups have the ability to conduct such tasks more effectively than individual entities.[36] SR systems can perform three main types of transportation and manipulation functions. These functions are referred to as pushing, grasping and caging. Pushing[134–139] can be conducted when external forces, such as friction and gravity, are applied to an object, and it is useful when an object cannot be grasped. A drawback with pushing is that it is hard to predict the movement of the robots and the object that is being pushed, particularly when the object is being pushed over uneven terrain.[136] Grasping incorporates form or force closure and can make it possible to lift objects on top of other objects or obstacles. In order to grasp objects, the grasping apparatus must be capable of resisting any external forces being applied to the object. Lastly, caging refers to the introduction of a bounded movable area around an object and allows SR systems to transport or manipulate objects without having to maintain direct contact with the object, making this approach simple and robust.[4,140,141] In contrast to grasping, pure caging does not enable objects to be lifted.

An analysis of literature that has been reviewed in this section is summarized in Table VII. One can observe that it is natural to incorporate functions that allow SR systems to transport and manipulate objects, as large groups are able to perform tasks more efficiently than individuals. One can also observe that the three main types of transportation and manipulation functions have their own associated strengths and weaknesses. It is therefore important to select the function that most efficiently solves problems in the application area at hand.

Literature relevant to how one can conserve and distribute energy resources among members of SR systems is reviewed in the following section.

3.5. The Energy Problem

Some of the greatest problems for swarm robotics are energy-related, as the whole system may shut down if energy sources are depleted.[77] Researchers have approached this problem in different ways, including minimizing the weight of robots and pre-positioning energy sources into the environment,[32] minimizing communication ranges of robots,[33] using directed rather than undirected connection links between robots,[21,74] minimizing oscillatory movements,[37] minimizing travel distances[142] and limiting the number of starts and stops performed by robots.[143]

Research on self-organizing sensors has also addressed the energy problems that occur when many individual “nodes” are incorporated into one system. Literature from this domain is therefore highly relevant to SR research. Relevant research on self-organizing sensors suggests that the energy problem can be addressed by reducing the difference in remaining energy among nodes,[47] promoting energy-efficient node placement through the use of self-organization,[144] reducing transmission power by minimizing the use of direct communication, sending data in simple wave forms[17,37,94] and putting nodes to sleep when they are inactive. How often nodes must be active depends on the application area. For example, nodes monitoring a forest fire must be more active than nodes monitoring a glacier. Some self-organizing sensor literature also suggests using specialized mobile nodes to collect and transport data. The idea is that the lifetime of the sensors can be extended by reducing the need for multi-hop communication, which easily depletes the energy of nodes in certain active regions.[40,113] The energy usage of the specialized mobile nodes can be reduced by minimizing their travel speed and ensuring that they cooperate in their harvesting efforts.[40,113] One may also recharge the specialized nodes at appropriate base stations when necessary without affecting the nodes responsible for addressing onsite tasks.[40]

An overview and analysis of the literature that has been reviewed in this section is presented in Table VIII. It is

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Table VIII. Addressing the energy problem.

Addressing the energy problem	
Analysis	
What is the energy problem?	Important considerations associated with the energy problem
• The whole SR system can shut down if energy sources are depleted.[77]	• The physical design, including weight and any action taken by the robots, increases energy consumption.[145]
Conclusion	
To prevent SR systems from shutting down prematurely, one should ensure that the physical design and any activities performed by the robots are energy-efficient. One should also ensure that the robots could be recharged.	

obvious that the energy problem is severe, as the whole SR system will shut down if energy sources are depleted. It is therefore important to ensure that both the physical design of the robots and any activity taken by the robots are energy-efficient. It is also beneficial to take measures, which ensures that the robots can be recharged.

In the following section we will analyse the reviewed literature and generate a list of issues that should be addressed to overcome the challenges associated with getting closer to the realization of a practical SR system for real world applications.

4. Analysis and discussion

Throughout this paper, we have discussed a series of challenges that must be resolved to get closer to the full realization of a practical SR system for real world applications. By reviewing and analysing seminal studies that tackle these challenges, we have drawn out a series of issues that should be addressed to overcome the challenges. These issues involve the following:

(1) Devising a hybrid distributed scheme that overcomes the drawbacks of pure centralized and decentralized systems.
(2) Devising a self-organizing SR system that can be supervised on an abstract level.
(3) Ensuring that devised mechanisms are scalable and robust.
(4) Generating and maintaining energy-efficient connected formations that support the task at hand.
(5) Ensuring that any robot can facilitate mapping and localization mechanisms.
(6) Incorporating path planning and obstacle avoidance mechanisms that do not depend on a particular specialized leader.
(7) Devising mechanisms that enable SR systems to manipulate and transport objects efficiently in the application area at hand.
(8) Taking measures to prevent the SR system from shutting down prematurely as a result of depleted energy sources.

The way in which the 148 reviewed studies relate to the above issues is illustrated in Fig. 1 (each issue is labelled in accordance to the above list). These particular studies have

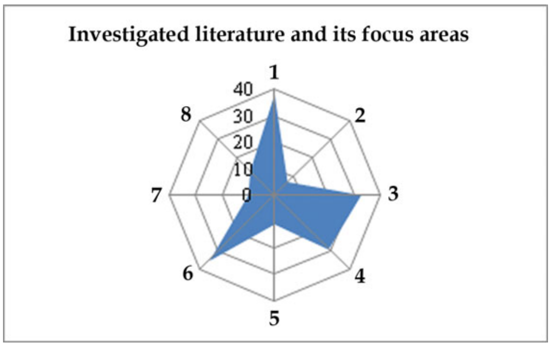

Fig. 1. (Colour online) How the reviewed studies relate to the issues that should be addressed to overcome the challenges associated with realizing a practical SR system for real world applications.

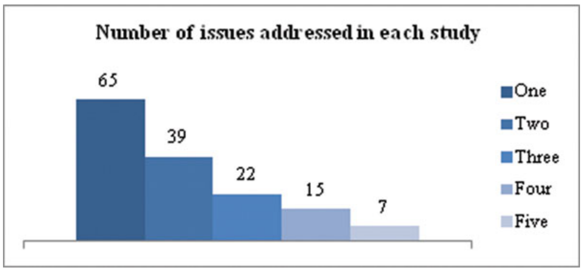

Fig. 2. (Colour online) The number of issues each study addresses simultaneously.

been selected because these are high-quality examples from the body of seminal studies relevant to swarm robotics, and provide a representative sample of the important research that has been conducted in the area. One can observe that about 77% of the studies focus on the four most well-studied issues, namely issues 1, 3, 4 and 6. One can also observe that only about 23% of the studies focus on the four least studied issues, i.e. issues 2, 5, 7 and 8. This shows that there is a wide discrepancy between the amount of research effort that has gone into the most and the least studied issues. It also shows that the future SR research should aim to investigate how these less studied issues can be addressed to provide a more complete understanding of how a practical SR system for real world applications can be realized.

The number of issues stipulated above, which each study addresses simultaneously, is illustrated in Fig. 2. One can observe that about 43.9% of the studies only address one of the eight issues, and that only about 4.7% of the studies focus on five issues. No study addresses six issues or more. This shows that a "complete" SR system for real world applications has not been synthesized as yet. Therefore, an opportunity exists for further research to be conducted in the SR domain. The results also show that future SR research should take more of the described issues into account simultaneously to get closer to a more complete SR system for real world applications.

5. Conclusion

This paper investigated how one can get closer to a practical SR system for real world applications. The paper commenced with a brief history of swarm robotics. Some of the strengths

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and weaknesses associated with SR systems were then presented along with a series of important application areas, including a brief overview of the various robots that can be incorporated into SR systems. Literature that investigates a series of challenges that should be tackled to get closer to an ideal SR system for real world applications was then reviewed. By analyzing the reviewed literature, we identified eight issues that need to be addressed to overcome these challenges. On the basis of further analysis, it was established that current SR research efforts mostly focus on only four of these eight challenges, and therefore fail to investigate the issues in a balanced manner. Future SR research work should therefore aim to investigate how the neglected issues can be addressed to support a more complete understanding of how a practical SR system for real world applications can be realized. It was also revealed that no SR study currently addresses more than five of the eight issues. Future SR research should therefore also aim to devise systems that address larger numbers of issues simultaneously.

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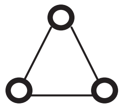
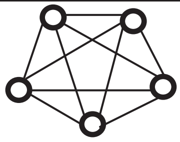
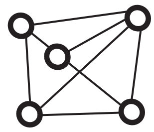
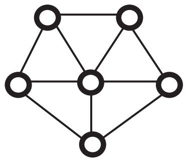
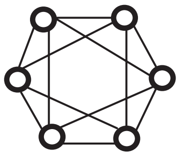
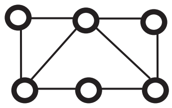
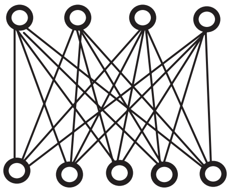
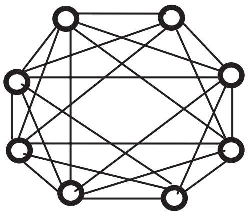
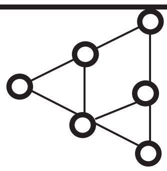
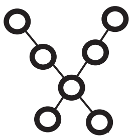
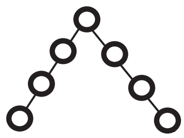
Appendix

Formations in Literature			
			
Name	Equilateral triangle/K3	K5	Bilateration
Method	Graph theory[74] and potential fields[107]	Graph theory[74]	Graph theory[74]
			
Name	Wheel	Hexagon/ C2/Circle	Rectangular/Quadratic
Method	Graph theory[21, 74]	Graph theory[21, 74] Focused-Coverage[41] and morphogenesis[27]	Graph theory,[101] Seed growing[63] and potential fields[108]
			
Name	Bipartite	C3	Line
Method	Graph theory[74]	Graph theory[74]	Graph theory,[101] Seed growing[63] and potential fields[106]
			
Name	Triangle	Four Pointed Star	Arrow
Method	Graph theory[101] and potential fields[107]	Seed growing[63]	Seed growing,[63] Morphogenesis[133,146] and potential fields[147]

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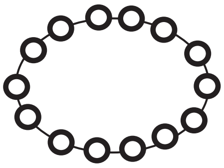
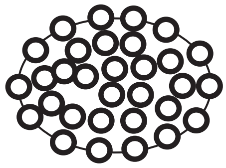
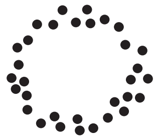
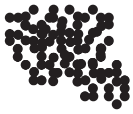
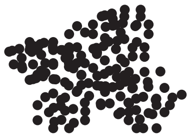
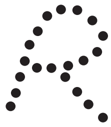
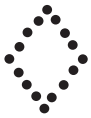
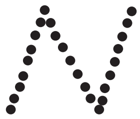
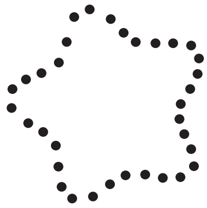
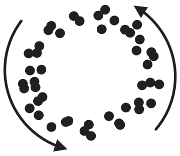
			
Name	Ellipse	Ellipsoidal Disk	Ring
Method	Voronoi diagram[33] and potential fields[148]	Voronoi diagram[33] and morphogen gradients[105]	Morphogenesis[27, 105] and potential fields[148]
			
Name	Lobed formation	Formation with controlled number of polygons	R-Shaped
Method	Morphogenesis[27]	Morphogenesis[27]	Morphogenesis[105, 133, 146]
			
Name	Diamond	N-Shaped	Five-pointed star
Method	Potential fields[107]	Morphogenesis[133]	Potential fields[108]
			
Name	Vortex		
Method	Inelastic collisions[109]		

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