A Survey of Robotic Swarms

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ABSTRACT
A lot of interest has been put in robotic swarm applications in the past. Despite this there is still a lot to be developed in the field. Robotic swarms are often inspired by nature, with the use of algorithms like the ant colony optimization, which is used for finding the shortest path from a point A to B. This is done with the same principle ants uses. The possibility to use simplified rules helps simple robots to achieve complex behaviors in a wide range of work assignments. In this paper an example of a robotic swarm design and robotic swarms will be discussed. The paper describes the principle of swarms in general and links this to a robotic application and how it is applicable in a real life scenario, in what scenarios the robotic swarm can be used, what the benefits and drawbacks are.

1. INTRODUCTION
Some researchers in robotics are trying to mimicking human intelligence, while other robotics researchers are taking inspiration from nature. It is not only the brains of animals and insects that they are trying to mimic but also their shapes and behaviour in unpredictable situations and environments. Swarm robotics draws inspiration from self-organizing behaviour observed in social insects like ants, bees and of other animals, called swarm intelligence (SI) [9].

One example of SI is bird flocking. By evading collisions, staying close to each other and aligning to local neighbours, birds in a flock avoid predators. These simple rules give rise to a very complex behaviour [1]. Fish schooling follows the same principle behaviour pattern. In social insect colonies, individuals may be very simple but when working together they can do remarkable things. For example, an object much too heavy for a single ant might not be for a group of ants working to reach a common goal. Ants are also very good at finding the fastest way to a food source from the nest by using pheromone trails [8].

This behaviour can be applied to robotics. The key concept is to get multiple simple robots following simple rules to carry out complex tasks. This is done by building a network of communication between the individuals in a robotic swarm, to enable them to share information amongst each other. Each individual coordinates by using de-centralized control and self-organization. This would imply there is no central ‘brain’ controlling the swarm, each robot needs to act independently [18]. They do so by following a set of simplified rules and algorithms. These rules and algorithms produce complex swarm behaviour. Algorithms like ant colony optimization (ACO) and particle swarm optimization (PSO) are some examples of algorithms that can be used in robotic swarm application [8], [19].

The paper is organized with section 2 containing a description of a swarm-robot’s (the S-bot) hardware design. Section 3 describes the robotic swarm design on a behaviour level. The concept of SI behaviour algorithms such as ant colony optimization (ACO) and particle swarm optimization (PSO), these are briefly mentioned and explained. Section 4 expands in some recent development of how far the field of swarm robotics has come today. Section 5 introduces some challenges of things that can very well be improved in the field of swarm robotics. The paper ends with a conclusion in section 6 were some benefits of swarm robotics are highlighted.

2. ROBOT DESIGN
The source of inspiration for a robot design is taken from nature and is shaped by environmental requirements. It gives some understanding of the general considerations needed to build a robot for robotic swarm applications. The general concept of a swarm robot design is that it should be very simple and relatively cheap to produce. For example, if one robot would get lost or broken beyond repair during a mission it would not matter much. Quantity is the key to success in a robotic swarm to effectively utilize SI algorithms. A robot should also be somewhat robust, simple and effective [3]. There are several designs in robotic swarm applications that satisfy these terms. One example of such a robot is the swarm-bot, called S-bot [15], [7], [14], [13]. The S-bot as the name illustrates is designed for swarm applications and is suitable for swarm functions. The S-bot is shown in figure 1. The S-bot is 19cm high, has a diameter of 12cm and weighs around 700g, about the size of a handball.
The S-bot design was intended to mimic the ant’s ability to grasp onto objects [3]. S-bots work as a team to find their prey and transport it back using the shortest path to the nest. The S-bot is a fully autonomous and mobile robot capable of clinging on to other S-bots similar to itself by using its grippers. By doing so the swarm can take any formation it wishes in the two dimensional space. The ability to do so makes the S-bots versatile. For example, the swarm can take a plough shaping formation to push an object forward or cling on to each other when crossing a gap much too wide for a single S-bot to cross [3], just like ants do [5]. The S-bot uses a two layer neural network onboard to teach the system and implement algorithms with simplified rules to produce the complex behaviours. Not all robotic swarm applications utilize neural networks [11].

![S-bot highlight](image.png)

**Figure 1. Shows the S-bot and its highlighted parts, image source “Teamwork in Self-Organized Robot Colonies” by S. Nouyan, R. Gross, M. Bonani, F. Mondada, and M. Dorigo [18].**

### 2.1 Manoeuvrability

Robots have different forms of liberty to move around in the environments they were constructed for. That manoeuvrability given is called degrees of freedom (DOF) [20]. In this case each moving part or joint is a DOF. The S-bot was given five DOFs [18] to maximize movement ability in respect to the S-bots size and power consumption properties. The S-bot uses two DOF’s for the traction system. It consists of a combination of two external wheels and a set of tracks, called treads. The treads gives the S-bot good traction in rugged terrain. This gives the advantage to overcome small obstacles. The S-bot uses another DOF to rotate the upper part of the S-bot, called the turret. The same DOF is used for the lower part, called the chassis. The 360 degree rotation gives the S-bot further freedom to grasp objects without having to reposition itself on the field.

On the S-bots front the grasping mechanism can be found, that is used to produce the gripping behaviour mentioned earlier. For this purpose, one DOF is used. An additional DOF is used to move the arm or joint where the grasping mechanism is attached to. These two DOF’s and associated parts are collectively called the gripper.

Even though the S-bot does not resemble an ant it is a very robust design. All DOF’s are set in motion by Direct Current (DC) motors. This gives enough manoeuvrability to perform the complex behaviours depending on the sensors, algorithms and rules implemented on the system.

### 2.2 Sensors and communication

To avoid collisions with other objects or sense edges the S-bot uses infrared (IR) sensors. When a collision is about to occur the S-bot emits a sound to warn the other S-bots using loudspeakers. The sound emitted is then received with one of the omnidirectional microphones on-board. Further sensing is used in the gripper; it has sensors to sense if a grip has been performed successfully or not.

The S-bot utilizes a Video Graphics Array (VGA) camera to capture images for the vision system to image process and colour detect. On the centre of the turret there is a vertically placed transparent tube with a spherical convex mirror on the top. This gives the VGA camera a good overview of the surrounding environment. See figure 2.

Communication is a key factor for any robotic swarm application. This is needed to give an individual in a robotic swarm better understanding of its environment and give a better sense of orientation. To communicate with other fellow S-bots the ring mounted on the turret is of importance. The ring is equipped with eight evenly distributed multi-coloured LEDs capable of emitting red, green and blue light. Different colours emitted by the LED-ring could mean different things depending on how the system is programmed. As an example red could indicate a request to grasp on to each other. There are other forms of communication like sending information in data packages wirelessly. As discussed in section 3.1.

The S-bot has many other sensors and functionalities on-board to further help it error adjust its DOF’s and manoeuvre with greater precision. For a more detailed overview of the design and hardware specifications see the paper by F. Mondada, L. M. Gambardella, D. Floreano, S. Nolfi, J.-L. Deneubourg and M. Dorigo, [3].

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2 Several S-bots were needed to move an object used as prey since it was much too heavy for a single S-bot.

3 The range of the IR sensors is limited to approximately 15cm.

4 An omnidirectional microphone means that it is sensitive to sound coming from all directions.

5 VGA means that the camera has a resolution of 640x480.
3. SWARM DESIGN

Looking at a swarm it works as a collective, by a common behaviour to complete a task rather than a robot performing an assignment. A swarm could be seen as one large entity. The design of a robotic swarm or multi-robot system consists of different highly integrated parts. Looking not at the physical design of the swarm robot, the swarm design is more the method a swarm functions with. Physical parameters are a condition of the swarm design, though it does not play a vital role in its construction. Emphasis is put on communication due to the fact that it is the main advantage of the swarm concept [10]. A swarm uses communication to share information among its members. If a robot gets ‘injured’, it could call out for assistance [6] from others in the swarm, if such approach was deemed effective. A single robot that finds a coveted object can call out for other robots in the swarm to assist in transporting of the object, if it is too heavy for one robot to move [6]. Communications is the key to designing a functional swarm where the advantages of a flexible team-work, much like the way humans work in groups, are visible. The issue can be encapsulated into the need of determining a functional way for the robots to communicate and react.

3.1 Communication

Communication is often desired to be wireless so as not to limit the moving capability of the swarm. The resources of the robotic platform can be limited, due to power restrictions [10], or physical size [11]. A natural approach is to lower transmission strength, processing power and memory capability. This would create a wireless ad hoc network suffering from intra-flow interference leading up to inefficient use of power [10]. To lower the hardware requirements, processing could be moved to a centralized system that would deprive the swarm of flexibility and fault tolerance. In the article “Robot Swarm Communication Networks: Architecture, Protocols, and Applications” [10], there is a suggestion to create a wireless communication network in specific areas to function as a backbone – a channel with high throughput for inter-robot communication, tracking and coordination. Such system could be supervised using centralized control software or a decentralized approach. The decentralized approach would have protocols to handle data fusion, swarm partitioning, energy efficiency and movement coordination. There is a need for network support such as communication load balancing, network reconfiguration, and quality of service. A functional decentralized system of this sort would result in very high fault tolerance, efficiency and flexibility, though it would still have high power consumption and need large processing capabilities. The centralized system would lower the computational and power restrictions, however lower the advantages given by the decentralized approach. Future work in this area could be of importance.

The flexibility and fault tolerance of a robotic swarm depends on high numbers of robots. In a system consisting of many robots working as a group the burden of performing a task does not depend on a single robot but rather depends on the group. A robotic swarm should be constructed to be able to handle a sudden loss of a robot. Therefore there should not be a single point of failure within the swarm. Centralized processing causes a single point of failure. An alternative could be to create several points of main processing. This would increase fault tolerance and increase flexibility due to load balancing. Such main nodes could be made mobile to follow the swarm in an area where a backbone is not available.

3.2 Navigation

Closely coupled to the subject of communication is the topic of navigation. For a robot as well as the whole swarm it is essential to understand the surroundings in order to facilitate interaction. Navigational systems for swarms are dependent on the individual robots sensors regardless of the type of navigation. Here the need for communication to exchange knowledge of the environment is essential. Different sensor systems could be used when readings are combined within the swarm. Several robots can work together to confirm a location, lowering fault probability. Robots could be designed to exchange mapping information [4], risk-analysis and the efficiency of different methods and strategies learnt through experience.

Pre-mapped environments have been a usual navigational method and give a high efficiency level already from initiation [11]. Pre-mapped environments could also be compared to location systems that use beacons or markings such as the cricket indoor location system [17].

Figure 2. A picture taken from the VGA camera onboard the S-bot, image from “Teamwork in Self-Organized Robot Colonies” by S. Nouyan, R. Gross, M. Bonani, F. Mondada and M. Dorigo [18].
These methods are efficient but can require extensive preparations depending on complexity and size of the environment. Most importantly they are inflexible and must be adapted to each environment they are applied in. Methods could be implemented to simplify the preparation method and make it faster, such as a technician scanning a simple map by a using elementary skill. Such speculations are interesting but flexibility like self-learning is one of the most important aspects, especially when focusing on tasks like exploration. The concept of SLAM [2], [4] (Simultaneous Location and Mapping) has proven to be a field of great stride. SLAM methods have shown great performance in multi-robot work-groups, such as swarms [4].

A SLAM produced map such as the one shown in figure 3 can illustrate an approximated image of the area explored by a robot.

![Figure 3. A SLAM map created by a robot running a stereo camera supported by a laser, images from "A sensor independent approach to RBPF SLAM – Map Match SLAM applied to Visual Mapping" by C. Schroeter, H.M. Gross [2].](image)

This technology used in swarms could fuse several maps from different robots to cover areas faster as shown in figure 4, two maps combined and later optimized offline in MATLAB for 12 seconds [4]. All mentioned methods touch upon some ways a swarm can communicate and navigate by. However, without a simple artificial intelligence (AI) and decision-making in each robot the swarm will not cooperate. A central question is to determine what is for the single robot to decide and what should be ‘discussed’ in the swarm or sent to a centralized AI. Using reactive algorithms is simple and limits the need of communication but do not use the full capability of a swarm. Market based algorithms are highly effective but require cognizance of the environment [11] and could benefit from a centralized AI due to the large amounts of states multiple entities could adopt. This would require large amount of computational resources. For hardware limited platforms, a hybrid method using reactive algorithms with collaboration on global communication or neighbourhood communication, have shown promise in applications where information of progress can be merged to avoid redundancy in a task [11].

3.3 Behaviour

Neural network implementations can be used to teach a robotic swarm system to behave according to given inputs from sensors and other on-board systems. Neural networks can be constructed in software or hardware. There are different ways of constructing a neural network, most of them relate to giving a winning strategy more credibility and therefore picking the solution with most credibility in a similar situation [12].

![Figure 4. (a) SLAM map from robot 1. (b) SLAM map from robot 2. (c) A fused map combining maps from robot 1 and 2 before optimization. (d) Fused map after optimization. Image from “Multi-robot SLAM with Topological/Metric Maps” [4].](image)
Neural training is a method that could improve problem solving and efficiency in a swarm. The technique builds on the concept of one robot teaching another [6]. A simple example of this is where positions of recharging are not known. If one robot finds a recharge station it could call out for others to gather and then lead them to the point of interest. The others could remember this point of interest, remembering the information when recharging is needed.

Ant colony optimization (ACO) is an algorithm that can be used in swarm robot AI. ACO is used to solve problems regarding path finding optimizations from point A to point B. The general concept of ACO is not surprisingly taken from the ant world. Ants are generally very good at finding the shortest path to a food source by using pheromone trails while exploring their environment. Imagine a set of paths leading to the same food source with each path having different travelling distances to it. Ants normally start to explore their environment by choosing a random path emitting their pheromone as they go. The stochastic outcome would lead to a stronger concentration in pheromone in the shortest path due to the fact that a higher concentration of pheromone is the more likely to attract more ants thus giving the result of the shortest path to the source. [8]

Birds in a flock use very simple rules to keep together and avoid predators. Each bird acclimatizes and corrects themselves according to their neighbours. Birds tend to fly in alignment with other birds within their spatial awareness. If the distances to other individuals becomes too great or close, the bird adjusts the distance keeping the group together. These sets of simple rules create a birds flock’s complex behaviour. Fish schools follow the same principle. To explain this behaviour the particle swarm optimization (PSO) algorithm has been of great importance and has been successfully implemented in reconfigurable walking robots [1], [19].

Combining algorithms like ACO and PSO with artificial neural networks can give us an efficient AI with learning capabilities. The ability to teach a system gives a huge advantage and more versatile system.

There are special applications where the robotic swarm’s borders to multi-robot scheme like self-assembling robotic swarms. Self-assembly is a concept of a swarm constructing a larger entity out of the smaller robots it consists of, the finished product acts as an individual robot even though it consists of many small robots and can be reconfigured according to changing requirements. In such a swarm robots could react and work as group communicating over a wireless network. After self-assembly to a larger more complex entity new design principles apply. In an assembled state, were individuals connect to each other new method of locomotion such as crawling, walking on legs or rolling can be used. Communication is another example where the method changes, in an assembled connected state it would be beneficial to run communication over a bus instead of wireless communication [5]. In this state the existence of a swarm is eliminated until the assembled entity disassembles.

These are some of the aspects of designing a swarm. A swarm will grant flexibility in its work but at the same time increasing the design complexity by equal extent.

4. RECENT DEVELOPMENT

Theoretical examples are interesting; real-life properties are often different. It can be hard to actualise an idea. Further work into robots and swarms can open new paths for the robotic swarm concept. In some cases the ideas are old but until shown possible to work practically often only admired as unreal dreams. Work that has shown potential for opening the way of new technology in inspection, surveillance and reconnaissance is the mechanical fly made by Robert J. Wood. He created a mechanical fly with a wingspan of 3cm [16]; it can be seen on figure 5. If such a mechanical fly could be equipped with an internal power supply, microcontroller and sensors it could become a very powerful tool for reaching small spaces while being difficult to detect. One could directly draw the relation to Alice shown in figure 6. Alice is a wheeled robot created for the evaluation of machinery inspection by N. Correll and A. Martinoli. Their creation was designed for the purpose of inspecting machinery, foremost aircraft turbines. Hassle with drive is related to rugged terrain. Correll and Martinoli propose magnetic drive wheels or adhesive drive wheels as a solution [11]. This solution is limited and if Woods robotic fly would become a reality it might be a very usefully in this application, moving freely in all directions.

Figure 5. The mechanical fly, image from “The First Takeoff of a biologically inspired At-Scale Robotic Insect” by R. J. Wood [16].

A field of great interest is self-assembly. A good example of a self-assembling robots is Sambot [5] seen in figure 7. Sambot is a robot that can potentially be used for search and rescue in collapsed buildings. It can reconfigure and move like a worm through scrambles and then reassemble as another suitable shape such as a walker if space is given. The technique is highly flexible where the swarm can adapt to the environment. The main differences in-between Sambot and S-bot self-assembling is Sambot
have the capability to self assemble in a 3D space. Sam-bot on the other hand is limited to smooth surfaces due to small thin wheels and it cannot assemble in arbitrary position, but only in perpendicular angles.

ROBOTRAK is an example of a real-time system for monitoring and controlling a swarm. This system was designed as a centralized system operating on a backbone like the Internet. Even if other software for these purposes has been made, the ROBOTRAK software differs from many others on the basis of it controlling and monitoring a swarm in real-time [10].

![Image 1](https://example.com/image1.png)

Figure 6. Alice, the inspection robot, image from “Multirobot Inspection of Industrial Machinery” by Correll and Martinoli [11].

5. CHALLENGES

Swarm robotics is an idea that in recent time has given rise to some interesting works. The whole field is open for discussion and development. Real life applications for robotic swarms using present technology are limited, where supervision, interactions with a swarm and energy accumulators are of large concern [11]. Systems like ROBOTRAK are needed to transform the concept of robotic swarm to a functioning and useful innovation. N. Correll and A. Martinoli touched on a very interesting topic. To increase safety and limit downtime in machinery, an intelligent sensor system would be effective. This system could consist of a swarm. This swarm could be placed inside a piece of machinery to work as an inspection tool. While the equipment is idle rather than using fixed sensors, indicating when a problem in the machinery has occurred [11].

![Image 2](https://example.com/image2.png)

Figure 7. Several Sambot’s that are in a self-assembled state moving like a worm. Image from “Sambot: A Self-assembly Modular Robot for Swarm Robot” by H. Wie, Y. Cai, H. Li, D. Li, T. Wang [5].

6. CONCLUSION

When committing to the development and dispatching of such complex systems as a robotic swarm the question must be raised what the benefits are and if it is worth the effort. In fact swarm technologies have the potential to lower costs and increase efficiency. This is due to the scalability, flexibility and fault tolerance of the swarm.

To reduce downtime in machinery, a robotic swarm can be used. Today much machinery needs manual inspection especially if the equipment is related to human safety. Downtime due to manual inspection can be lowered using a swarm of robots working in parallel, reaching machinery that would require cameras and dismantling of parts [11]. Remote equipment could be reached by means of a swarm. An example of this could be power line inspection where a long distance of cable needs close and visual inspection. A swarm could travel along the power lines checking them for damage. If damage is found a larger separate robot could be sent for repairs. This would speed up the inspection process, increase efficiency and lower cost.

When searching for something it often requires covering large surfaces. Whether it is under water, from the air or on the ground, more units searching imply faster coverage due to its scalability. Here the use of robots can lower cost by replacing manned search. Were robots search with a range of sensors beyond human capabilities. This would implicate in the event that the desirable object or objects are humans that lives could be saved.

These swarms could also be used in hazardous environments that are unsuitable for human interaction. Several robots also have the capability to transport objects as a group giving support one robot could not achieve [6], [18].
In surveillance of buildings and larger aerials, swarms give better coverage, fault tolerance and navigation than single robotic surveillance. In addition a swarm, compared to human surveillance gives lower costs [10].

From these applications we can see some of the advantages of applying a robotic swarm to an assignment that has high cost and is difficult to perform for humans. If the assignment requires a need for scalability and fault-tolerance the gain is even higher.

7. ACKNOWLEDGES
T. Ottes, P. Lenander, A. Domfors, L. Lagerholm, whom read the first sketch of this paper and gave constructive comments, helping the revision.

8. REFERENCES