A Review on Swarm Robotics: From Concept to Development

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Abstract— **Swarm Intelligence (SI) is the collective behaviour of decentralized, self-organized systems inspired from natural biological systems such as ant colonies, bird flocking, animal herding, bacterial growth, and fish schooling. Swarm Robotics (SR) is an emerging application of swarm principles to robots, it is the study of how to design groups of homogeneous, small and cheap robots that mimicking insects and animals and acts together for robust, scalable and flexible swarm robotic systems. Swarm robots operate without depending upon any external control and infrastructure, the behaviour of robots depends on interactions between robots and between the robots and the environment in which they act. Swarm Robotics has effectively applied in tasks that are risky and difficult for human being or single robot. This Paper is a review of swarm robotics from origin to its future. It contains discussion on introduction to swarm robotics, design of robot swarm, design of robotics collective behaviours, and interaction mechanism and future of swarm robotics.**

***Keywords*— Swarm intelligence, Swarm Robotics, Swarm robots, Collective Behaviour, Source of inspiration.**

I. INTRODUCTION

Swarm Robotics is a multi robot system which consists of a large number of simple, homogeneous, small sized physical autonomous robots that follows the principle of swarm intelligence [1]. Swarm Intelligence is the study of are trying how collection of animals and insects, such as ants, bees, flocks, herds and schools, moves in a way that they appear like they are organized by some external sources, but in reality they are self organized by some biological forces [2]. They do their task collectively by keeping an eye on each other's movement. This type of coordinated movement in insects is termed as "Swarm" and when this coordination of movement is performed by some group of robots then it is called as "Swarm Robotics" inspired by colonies of ants and swarms of bees.

The embedded system is the software or dedicated computer system that works within mechanical and electrical system [6]. Similarly Swarm robotics can also be viewed as embedded system that has a physical body works on intelligent programming. Swarm robotics is study of creating large amounts of homogenous, small size, cheap and simple robots that work together and mimic natural insects and animal's biological behaviour to perform complex tasks.

Swarm robotics is an approach to robotics that emphasis many simple robots instead of one single complex robot. This simple group of robot coordinates by taking inspiration from the system-level functioning of social insects and animals which exhibit three characteristics to robot swarms [5], for achieving measurable quality in swarm robotics system must have these main characteristics.

- Scalability: the control architecture can be kept exactly the same from a few units to thousands of units.
- Flexibility: units can be dynamically added or removed, they can be given the ability to relocate and redistribute themselves in a self-organized way.
- Robustness: the resulting collective system is robust not only through unit redundant, but also through unit simplicity and an appropriate balance between exploitative and exploratory behaviour.

In this paper section II contains Design of swarm robots that includes Physical requirements to build a robot and mode of operation that should be performed by robots, section III puts a focus on design of collective behaviours in swarm robotic systems, section IV is discussion on interaction techniques by which robots Communicates with each other to survive in a changing environment and last section V shows the survey of swarm robotics projects and its future scope.

II. DESIGN OF SWARM ROBOTS

The swarm robots are like blood of swarm robotic systems. Like any other robot, a swarm robot has two main organs; hardware and software. Software is the brain of the system. It gives a simulation environment to the functioning of the robot. In essence, it is the brain of the system. The hardware brings into action, directions simulated by the software. Key features of swarm robots are, homogenous, small size, cheaper, reconfigurable and parallelism.

A. *Physical Design*

The development of robot is inspired from nature and shaped by environmental requirements. The general concept of a swarm robot design is that it should be very simple and relatively cheap to produce because it needs large and generally large number of robots. Swarm robotics generally used in a risky environment so if robot would get lost or broken beyond repair during experiment it would not matter much. Mass production of robots is essential for the deployment of swarm robotic systems Because a large number of robots is the key to success in a robot swarm effectively utilize SI algorithms [6].

Development of swarm robot is similar as development of signal robot [7]; swarm robot requires all basic components that are necessary to build a simple robot. Mobility, Interconnection, sensors, communication, and CPU, controller are key components to build swarm robots.

1) Mobility: The Robots have different power of choice to move around in the environments. The mobility of the system is ensured by a combination of the following modules [7][8]:

TABLE I
PHYSICAL MODULES USE TO BUILD A ROBOT

Module	Used for
Treels (Wheels & Tracks)	-Combination of two external wheels and a set of tracks. -Gives the robot good drawing in rough area surface. Advantage to overcome small obstacles
Turret and Chassis	-Rotation of the upper part and lower part respectively, of the robot -Use to move an object
Grasping	-Used to produce the gripping Behaviour.
Gripping	-Used to move the arms or joints

All these modules are controlled by a direct current (DC) motors so that the robot can freely move in the environment and easily rotate on the spot. This structure enables a very good mobility thanks to the position of the wheel and their diameter larger than the track height.

2) Sensors and Communication: To avoid collisions with other objects or sense edges Communication between robots is necessary. Robots communicate with each other using sensors. Each robot is equipped with sensors and communication devices to detect and communicate with other robot. These devices are implemented using a color omnidirectional camera, 16 lateral and 4 bottom infrared proximity sensors, 24 light sensors, a 3 axis accelerometer, two humidity sensors as well as incremental encoders and torque sensors and many more

3) CPU and Controller:
The control strategy of the robot consists of distributed algorithms based on local information and simple self-organization rules inspired upon ant colony behaviours. The type of experiment that will be conducted on this system are very similar to biological experiments, will also need very good monitoring and collection of large quantities of data for software development and experimental analysis [8]. CPU Implementation of any consists of microprocessor board, micro controller, operating system for supporting processor , RAM for running main programs, FLASH drive, USB master and slave interfaces, serial interface, IC bus and two Compact Flash slots.

B. Mode of Operations

The swarm will be able to operate in several autonomous modes. Robots changes their mode autonomously on the bases each other's behaviour and requirement of the system. These modes are as follows:

1) Non-Communicative Swarming: In non-communicative mode the swarm consists of homogeneous, but anonymous robots, the latter means that the robots are able to recognize another robot as a robot, but they cannot identify other robots as a particular individual with a unique name.

2) Communicative Swarming: In non-communicative mode the input values for the control model originate from the robot itself. In communicative mode the robots may use the information of all other robots.

3) Networking: The robot swarms have to build and maintain communication network in the case of wireless network the robots have to stick to the strong signal for better performance. In swarming searching for a wireless signal and building a network transfers into what is called ad-hoc networking. In ad-hoc networking the topology of the network changes according to the environment

4) Olfactory-Based Navigation: The robots are provided with a 'nose' to measure air concentrations [9]. This enables applications in surveillance for environmental pollutants, the detection of hazardous gases and plume tracking, but also navigation on self-produced odors. Communicative mode and non communicative mode, both supports this type of navigation.

5) Assistive Swarming: In telerobotics several humans may operate one robot. It is basically one human being cooperating with other robots. There are two types of swarming one is human is leading the swarm and other is the swarm is guiding the human being.

III. COLLECTIVE BEHAVIOUR

Once the physical robot built next is to implement software that directs the robot to their action. The swarm robotic system mimics the collective behaviour of natural insects and animals. Any change in the structure, environment or function of an entity in swarm must be adapted by other entities in the same swarm because they allow them to survive more effectively in the swarm robotic system. Individual behaviours are iteratively adjusted and tuned until the resulting collective behaviour is obtained is the key approach of designing collective behaviour among swarm robots.

To design any collective behaviour among swarm robots, requires solving two questions; first is the collective behaviour inspired from which natural insect or animal, and the second is which method or approach is best suitable to achieve that behaviour. Source of inspiration is discussed in following section.

A. Source of inspiration

In Robotics environment every process is artificially developed from the Implementation of Robot to problem solving approach inspired from below given mechanism.

*1) **Particle swarm optimization:*** In computer science, Particle swarm optimization (PSO) is a computational method that optimizes a problem by iteratively trying to improve a candidate solution with regard to a given measure of quality. PSO optimizes a problem by having a population of candidate solutions, here known as particles, and moving these particles around in the search-space according to simple mathematical formulae over the particle's position and velocity [10].

2) Ant colony optimization: Ant colony optimization or ACO is a probabilistic metaheuristic optimization algorithm that can be used to find approximate solutions to difficult combinatorial optimization problems. In ACO artificial ants build solutions by moving on the problem graph and they, mimicking real ants, deposit artificial pheromone on the graph in such a way that future artificial ants can build better solutions. ACO has been successfully applied to an impressive number of optimizations. It is based foraging for food by ant colonies [11]

3) Artificial bee colony algorithm: Artificial bee colony algorithm (ABC) is a meta-heuristic algorithm based on the foraging behavior of honey bees [12]. The algorithm is divided bees in three types employed bee, onlooker bee and scout bee. First two types of bees exploit the sources by local searches in the neighborhood of the solutions selected based on deterministic selection in the employed bee phase and the probabilistic selection in the onlooker bee phase. In the scout bees which are an analogy of abandoning exhausted food sources in the foraging process, solutions that are not beneficial anymore for search progress are abandoned, and new solutions are inserted instead of them to explore new regions in the search space. The algorithm has a well-balanced exploration and exploitation ability.

B. Approaches to design Collective Behaviours

Probability finite state automata technique and virtual physics based design are classical approaches to design collective behaviour among robots. Learning and soft computing approaches are new emerging techniques that still in ongoing research phase.

1) Probabilistic Finite State Automata: In swarm robotics, an individual robot does not plan its future actions, but it takes decisions only on the basis of its sensory inputs and/or its internal memory [13]. One of the most adopted behaviour design methods to obtain such behaviours is the use of a particular class of finite state machine: probabilistic finite state machines (PFSMs). In PFSMs, the transition probability between states can be fixed or can change over time. The transition probability is fixed when a single probability value is defined and used throughout the execution of the collective behaviour. The transition probability is not fixed when it is defined through a mathematical function of one or more parameters of the system

2) Virtual physics based design: The virtual physics-based design method is based on physics. Each robot is considered as a virtual particle that exerts virtual forces on other robots. It uses the concept of social potential fields and artificial potential field and proposed a most general a virtual physics-based design method called physicomimetics framework. Virtual physics-based design assumes that the robots are able to perceive and distinguish neighbouring robots and obstacles, and to estimate their distance and relative position. Each robot computes a virtual force vector [14] :

$$\mathbf{f} = \sum_{i=1}^{k} f_i(d_i) e^{j\theta_i} \qquad \textbf{(1)}$$

where *fi* and *di* are the direction and the distance of the i^{th} perceived obstacle or robot and the function *fi(di)* is derived from an artificial potential function. In this method all interactions of the robot with other objects in the environment represented as vectors either attractive (e.g. moving towards a goal) or repulsive (e.g. moving away from obstacles) vector. This vector representation of these forces is computed locally from the viewpoint of the robot and used as the action of the robot which makes these studies fully distributed. No global map is generated. Other objects in the environment are assumed to be applied virtual forces to the robot selected. The robot computes the average force computed by its observations and moves towards the direction of average force. The force exerting on a robot from an external object depends on two things: the bearing and the distance to the external object both these parameters can be computed from local observation.

3) Reinforcement learning: Reinforcement learning is a set of methods that automatically design individual behaviours for robots in a swarm. RL traditionally refers to a class of learning problems: an agent learns a behaviour through trial-and-error interactions with an environment and by receiving positive and negative feedback for its actions [14]. In RL, the robot receives a feedback for its actions and the robot is to learn automatically from that feedback and an optimal policy, that is, the optimal behaviour mapping robot status of robot actions. Reinforcement learning studies divided into two categories: the studies which use local reinforcement and the ones which use global reinforcement. Local learning can be seen as a loosely coupled distributed reinforcement learning system [15]. Global learning uses combination actions, the action to be taken by all other robots should be taken into account when a robot determines their own actions, which can be seen as a tightly coupled distributed reinforcement learning system[15].

4) Soft Computing Approach: Swarm robotic study follows two approaches using soft computing techniques [16]. The one is the classical approach studies with neural networks considers the neural networks as a generalized mechanism of connecting all possible connections between the nodes in the hidden layer and the ones in the output layer. All the links have been evolving connection weights having the values between -1 and 1, while the structure of the network does not change for all the generations.

The other approach uses genetic algorithms to evolve the weights of a neural network to obtain a desired behaviour with a fitness function appropriate to the problem is the Topology and Weight Evolving Artificial Neural Network (TWEANN) approach.

C. Collective Behaviour Design

As said earlier in this section that to design any collective behaviour among swarm robots, requires a source of inspiration and method or approach to employ that behaviour. Collective behaviours that can employ in a robot swarm with their source of inspiration and best suitable method to employ that behaviour[17] .

1) Aggregation: The aggregation is to group all randomly placed robots in an environment in a specific region of that environment.

- Biological Inspiration: bacteria, cockroaches, bees, fish and penguins.

- Development Method: probabilistic finite state machines (PFSMs) or artificial evolution.

2) Pattern Formation: Pattern formation behaviour robots form any kind of patterns suitable to their work. One basic requirement for forming a pattern is to keep specific distances between each other.

- Biological Inspiration: spatial disposition of bacterial colonies and the chromatic patterns on some animal.
- Development Method: physics distribution and crystal formation using virtual physics-based design or reinforcement learning.

3) Chain Formation: In this type of behaviour robots connect themselves to form a chain for this first they need to position them in order to connect two points.

- Biological Inspiration: foraging ants
- Development Method: probabilistic finite state machines (PFSMs), virtual physics based design, artificial evolution and reinforcement learning.

4) Self-assembly and morphogenesis: In swarm robotics Self-assembly is the process by which robots physically connect to each other for forming some other object such as bridge, ladder etc. Morphogenesis is the process that leads a swarm of robots to self-assemble following a particular pattern, and can be used by the swarm to self-assemble into a structure that is particularly appropriate for a given task.

- Biological Inspiration: ant's activities such as bridges, rafts, walls and bivouacs.
- Development Method: Self assembly using probabilistic finite state machines & Morphogenesis using artificial evolution or of probabilistic finite state machines.

5) Object clustering and assembling: In this type of behaviour the robots explore the environment at random and react in different ways to the discovery of available objects or of part of the cluster/assemble to create

- Biological Inspiration: social insects such as ants exhibit brood clustering and exploit natural occurring gradients such as temperature gradients.
- Development Method: probabilistic finite state machines

6) Collective exploration: This behaviour is a combination of two behaviours: area coverage and swarm-guided navigation. To deploying robots in an environment in order to create a regular or irregular grid of communicating robots is area coverage behaviour.

- Biological Inspiration: social animal's common behavior Area coverage and navigation such as ants use pheromones trails.
- Development Method: probabilistic finite state machines or network routing protocols or natural systems.

7) Coordinated Motion: coordinated motion can be very useful as a way to navigate in an environment with limited or no collisions between robots and as a way to improve the sensing abilities of the swarm.

- Biological Inspiration: social animal's activities such as flocking in a group of birds or schooling in groups of fish by which animals gain higher survival rate
- Development Method: virtual physics-based design and artificial evolution

8) Collective Transport: This type of collective behaviour is implemented in robots in order to transport an object.

- Biological Inspiration: swarm intelligence principles of ant colony
- Development Method: probabilistic finite state machines (PFSMs) or artificial evolution.

9) Collective Decision-Making- Consensus Achievement: allow all robots to agree on one choice among different alternatives. But the choice should be in the favor of system.

- Biological Inspiration: many insects spices such as ant decision making to find the shortest path, bees decision on best nest location among several possibilities
- Development Method: according to their communicating methods.

10) Collective Decision-Making- Task Allocation: In these types of collective behaviour the robots distribute themselves over different tasks in a way that benefits the system.

- Biological Inspiration: ant and bee colonies, for example part of the swarm can perform foraging while another part looks after the larvae
- Development Method: probabilistic finite state machines (PFSMs)

11) Collective Fault Detection: Robot who has this type of behaviour can able to automatically detect failures and faulty behaviour in the system. This failure might be of hardware failure or might be of software failure.

- Biological Inspiration firefly synchronization.
- Development Method: probabilistic finite state machines (PFSMs), artificial evolution, or reinforcement learning.

IV. INTERACTION

A Communication mechanism used by swarm robots can be classified in three categories interaction via sensing, interaction via communication, interaction via environment [18]. The main question arises that how discrimination of interaction via sensing and via communicating is done. This is done by looking at the aim of information sender side; if a sender intentionally sends information then it is categorized as interaction via communication and if the receiver automatically gets information from the behaviour of senders is categorized as interaction via sensing. The studies of these categories are given below.

A. *Interaction via Sensing*

As said above, if two robots are communicating without any direct communication only by just sensing each other's activity is known as interaction via sensing. If two robots interacting to pull a stick and sensing each other's action in a limited way, this work are considered as "interaction via sensing". Interaction via sensing is inspired by the feature of animals in nature called kin recognition. With the help of kin recognition, animals can behave differently to their kin, work together to accomplish some tasks, and protect themselves from their enemies better. Kin recognition can consider as a kind of minimalist communication mechanism since just by discriminating the kin and observing their behaviours, the robots can manage patterns such as aggregation, chain formation and cooperatively stick pulling in swarm robotics.

B. Interaction via Communication

In this type of categories the robots communicate directly with each other by broadcasting or one-to-one communication. One to one communication is done between two robots using by identification of robot. But Identification of the robot may reduce the scalability and flexibility of the system. Nouyan and Dorigo [19] implemented a chain formation behaviour.

Initially the robots search for another chain members or the nest. Once a robot finds a chain member or the nest, it becomes a chain member depending on two predefined timeouts. The robots distinguish chain members and the nest based on the color of the LED ring around their body. A chain member can have three different colors: blue, green and red. It activates the color blue, if it connects to the nest or to a red chain member. It activates the color green, if it connects to a blue chain member and color red otherwise. This coloring mechanism allows robots to find the direction of the chain. Since having a long chain instead of a chain with several branches is preferred.

C. Interaction via Environment

In this category the robots used the environment as a communication medium. This type of communication mechanisms is inspired from biology like communication via pheromones in ants [20]. The ants communicate with each other through chemicals called pheromones. The communication scheme is simple in this approach, but the physical implementation of it is not so easy because of the difficulty of creating special environments allowing communication between agents. This approach uses only a simulation of this communication scheme with the help of a short range wireless communication mechanism.

V. FUTURE SCOPE

Robots are going to be an important part of the future. Single robot is a most attractive field of study and research, But now this is about groups of robots, it will be the next step of the single robotics system, although both have different type of application domains but both are used to make a human's task easier. Swarm robotics is an approach to collective robotics that has received a great deal of attention in recent years. Swarm robotics aims at developing systems that are robust, scalable and flexible. Swarm robotics have several possible applications, including: exploration, surveillance, search and rescue, humanitarian demining, intrusion tracking, cleaning, inspection and transportation of large objects [15]. Here the brief discussion on the future of swarm robotics in some emerging application is given.

A. Mobile Surveillance System

In mobile surveillance, swarm robotics shows its own efficiency apart from other surveillance systems. Surveillance systems are often needed in areas too hostile or dangerous for a direct human presence. The field of robotics is being looked to for an autonomous mobile surveillance system [21]. Sometimes the area under surveillance is unknown and dangerous, manually installing stationary sensors is not feasible and then sensors must be mobile. The area is also assumed to be too large for a single agent's sensors to find a target effectively. The system cannot depend upon the presence of any one robot to be a communication hub or leader; therefore, the control must be completely distributed. To provide this distributed architecture swarm robotics is the best solution.

B. Swarm Controlled Mobile Wireless Sensor Networks

Protocols of Wireless Sensor Networks (WSNs) commonly look to implement the best route for packages almost randomly generated until they arrive at the sink node. In mobile WSNs the sensor nodes are able to move and the routing task is more complex. One way to implement mobile WSNs is using small mobile robots to carry the sensing elements by the sensing area. The algorithm that controls the movement of the robots can be based on a swarm approach [22].

In a typical swarm of robots only the communication between the robots is implemented to ensure the swarm behaviour, but it is not enough to make the swarm act as a WSN. This needs unified coordination-communication strategy to control the swarm of robots so that it can act as a WSN.

C. Inspection of Complex Engineered Structure

A potential application of swarm robotics is the inspection of complex engineered structure such as Turbines [23]. Turbines are the critical element in power plants and jets, where they face extreme wear and tear. Downtime, however, leads to considerable cost and safety problems. In order to ensure the economical and safe operation, the turbines need to be inspected visually using bore scopes at regular intervals. A process that performs inspection when the turbine is idle, which design using swarm robotics. We can apply this type of swarm robotics mechanism in inspection other engineered structures such as engines, boilers, avionics, mechanical and electrical machineries.

D. Underwater Swarm Robots

The goal of underwater swarming is to create small, relatively cheap, underwater robots that allow underwater tasks without the use of large, expensive, existing underwater robots. Each robot will be autonomously controlled and will use swarm Intelligence to share tasks and information among other robots and an underwater environment. The applications of this can include mapping, imaging, environmental monitoring, surveillance, and exploration. The future is in developing or tries existing communication devices that can effectively transfer and receive data wirelessly underwater [24].

VI. CONCLUSION

Swarm robotics is the study of how to design groups of simple, homogeneous, small sized physical autonomous robots that operate without relying on any external or centralized control. The main difficulty in designing swarm robotic systems is to design collective behaviour inspired by swarm intelligence. To achieve desirable behaviour, it is necessary to manage the effect of individual robot characteristics scalability, flexibility and robustness have on the collective behaviour. This Paper has discussed about Physical design of swarm robots, Methods that used to implement collective behaviour, type of collective behaviours along with their source of inspiration and effective approach to implement that behaviour. As swarm robotic system doesn't rely on any external control interaction between robots and environment is necessary. The paper gives a brief discussion on interaction mechanism that employ by robots for effective communication. Single robot is a most attractive field of study and research, but swarm robotics is about groups of robots. Swarm robotics have a very bright future because it is above the single robotics mechanisms. This paper also discusses the future of swarm robotics under swarm emerging application such as underwater swarming, mobile surveillance systems.

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