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A Survey on Swarm Robotic Modeling, Analysis and Hardware Architecture

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Abstract

The present paper studies, the progress in the research of nature inspired swarm robotics. Swarm robotics is a robotic technology inspired from the nature (natural swarms). In this, an artificial intelligence aided coordination approach is used for the self-organization and decentralization of multiple robots. Being a promising centralized approach with fault tolerance, redundancy and scalability potentials, they can even work when it is technically infeasible to set up the infrastructure required to control the robots in a centralized way. But the design of individual robot level practice to achieve a desired collective behavior is really difficult as it is hard to predict the simultaneous interactions between large numbers of individual robots. In order to explore the possibilities to make a better progress in this technology, the existing modeling, analysis methods and the challenges has to be studied first. Followed by this, a study on swarm communication and the hardware units including sensors and actuators was done. Further the existing swarm platforms are compared based on hardware detailing, advantages and limitations. This comparative study can pay way to a better design of a multi-robot system for the applications like rescue operation, surveillance, oil spills, military applications etc.

Keywords: Swarm robots; self-organization; decentralization; centralized approach; Fault tolerance; modeling; analysis; hardware architecture; collective behaviour.

1. Introduction

Over the past decade, many research and developments have come across the field of multi robot systems. Multi-robot frameworks have favorable circumstances: fault tolerance, giving adaptability to the errand execution or make use of the advantages of distributed sensing, actuation, self- reconfiguration etc. This system can be a group of homogeneous or heterogeneous robots. The homogeneous multi robot system, the swarm, is studied in this paper.

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Swarm is emerged from the studies on biological beings (insects like bees and ants, birds, fishes) and from the field of Swarm Artificial Intelligence (SAI). Hence, the Swarm robots are basically a group of identical small robots with little capabilities individually with which they work together to achieve a desired global goal with the help of robot-robot and robot-environment interactions. There exists many applications based on the type of tasks they have to do like: aggregation (forming groups), foraging (collecting and delivering something to a destination, in the same way how ants collect food), exploration (in order to explore maximum area, they distribute themselves), flocking (highly coordinated group behavior like birds and fishes), clustering and sorting (nest building of wasps and termites) [40]. A few of the natural swarms are shown in Figure 1.

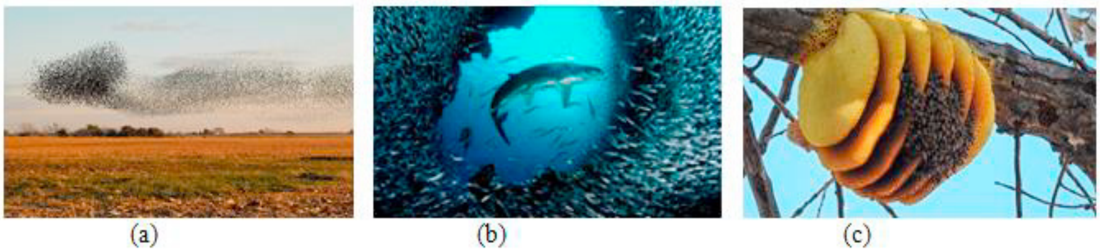

Fig. 1. Examples for natural swarms (a) flock of birds; (b) school of fishes; and (c) colony of honey bees.

Even though swarm robotics has varied range of applications, this paper dedicates concentration to swarm behavior study and hardware architecture. The paper is structured as follows; the existing modeling and analysis methods in swarm are discussed in Section 2. The hardware architectural details of major swarm robots are compared and their merits and demerits are discussed in section 3.

2. Swarm design and analysis methods

In swarm robotics applications, there is no clear formula for designers that will produce a certain global behavior X based on local behaviour Y or vice versa [62]. Henceforth, design of swarm frameworks has a tendency to be an experimentation procedure. Hence it is essential to keep tuning the robot system design until the desired behaviour is reached. Generally, swarm robot design can be done by: behavioural and automatic methods**.** Behavioural analysis is an iterative method to achieve the desired collective behaviour of the swarm [3]. Most of the behaviour based design strategies utilize either Probabilistic Finite State Machine (PFSM) or Virtual-Physics based design techniques whereas automatic design methods comprise reinforcement learning and evolutionary robotics. The Probabilistic model is one of the diagram approaches used as a piece of swarm structures to consider their lead and was first introduced by Minsky in 1967 [5], [4]. There are two kinds of models to PFSMs, one where likelihood is fixed and is applied all through the system until it converges to a solution [6]; the other one is a variable probability in light of a numerical model (mathematical model) changing in light of inputs from various robots and the environment. PFSMs were utilized to create real aggregate practices, for example, aggregation [10], chain formation [11] and task allocation [12, 13]. In an investigation of collective decision making and task allocation, reaction threshold work appeared in[7, 13, 8, 9] has been presented in swarm apply autonomy and was utilized to break down the conduct of a swarm of social bugs where the threshold is the likelihood for an agent to perform a task based on perceived stimuli. Whereas the virtual physical science-based plan was produced in a way where every individual in the swarm is considered as a virtual particle that applies forces on different particles in the environment. Artificial potential field concept is adopted by many researchers where robots are considered as virtual forces, obstacles as virtual repulsive forces that repel with robots, and the goal as a virtual attractive force that attracts other robots towards it [14, 15]. The automatic design method, reinforcement learning (RL), is a learning system for the operator through experimentation (trial and error), based on spatial credit assignment [16, 17]. Neural systems [18] and fast learning algorithms [19] were utilized to lessen the huge size of the state space [20]. However, nobody has addressed the issue of non-stationary environment in swarm robotics utilizing RL plan strategies whereas, evolutionary robotics have taken inspiration from the Darwinian principle of evolution. It is used to test the effectiveness of design methods [21, 22] and to provide scientific proofs [23, 24]. They are mostly applied on homogeneous systems, where same fitness function applied to the whole system. Virtual force functions, finite state machines and neural networks are used to represent individual behavior.

Once a design is made, it has to be verified to study the effectiveness on the behavior of the system. These verification methods are divided into behavioral analysis and real robot analysis methods. In behavioral analysis using rate and differential equations, the collective behavior can be described from the individual behavior using Rate equations with simulations. V-rep is one simulator used and many more are available in [25, 26]. In the case of mobile robots design with multi body dynamics, ADAMS [67, 68] can be used. In classical control and stability theory based analysis, simulations based on strong mathematical equations are used, making it the best available method to model the behaviour of the swarm. Still the absence of global information is a challenge to model. Discrete-time and discrete-event dynamic systems were used to model swarms of robots in 1D [28, 29]. Lyapunov stability theory was used to demonstrate that the presence of noise in a swarm environment will not hinder coherent foraging tasks [30, 31]. Additionally, a linear discrete system was used to model the behaviour of a swarm [32]. Moreover, a sort of delay differential equations were used for modeling task allocation [33].When it comes to real robot analysis, hardware prototypes are made to validate the simulations. Principle objective of a large portion of related work is to demonstrate broad experimentation where different runs [34] are done and the normal is concentrated to validate properties of the framework [35, 36]. Moreover a collection of models for swarm design are listed in Table 1.

Table 1. Various models in swarm design [40].

Mathematical model	Modelling equation	Remarks
Markov'sChain Process	$\Delta p(n,t) = p(n,t+\Delta t)p(n,t)$ $= \sum_{n'}^{1} p(n,t+\frac{\Delta t}{n'},t)p(n,t) -$ $\sum_{n'}^{1} p(n',t+\frac{\Delta t}{n'},t)p(n,t)$	P(n,t)= Probability of an agent to be in the state n at time t, delta-t is the Transition probabilities, probability of state *n'*
Rate-Equation (Time-Continuous)	$\frac{dNn(t)}{dt} = \sum_{n'} w(\frac{n}{n'},t)Nn'(t;) -$ $\sum_{n'} w(\frac{n}{n'},t)Nn(t)$ $w(n/n';t) = \lim_{\Delta t \to 0} \frac{p(n,t+\frac{\Delta t}{n'},t)}{\Delta t}$	Where n , n' = all possible states at each instant, Nn = average fraction of agents in state n at time t.
Geometric Probabilities	$R_i = (vWs / As)g_i$ $P_i = r_i T$	As is detection area of the object, v is a mean robot speed, Ws robot's detection width, gi geometric probabilities, r_i, encountering rate. In time discrete p_i is encountering probabilities (per time step).
Differential equations	$\frac{dM(t)}{dt} = -\alpha_r Ns(t-\tau)[Ns(t-\tau)+N_0]$ $-\alpha_r Ns(t-\tau)[Ns(t)+N_0]$ $\frac{dM(t)}{dt} = -\alpha_p Ns(t)M(t)$	$Ns(t)$: no of robots in search state at time t, $Ns(t)+Na(t)=N_0$ is the total no of robots, $M(t)$: no of uncollected pucks, *t-t* exit the avoiding and resume search.a_r be the rate of detecting another robot, a_p: rate of detecting the puck.
Probabilistic finite state automata	$P_w = \frac{A_w}{A_A}, P_R = \frac{N_r.A_R}{A_A}$ $P_{G1}(t) = N_{G1}(t).\frac{A_s}{A_A}$ $P_{G2}(t) = N_{G2}(t).R_{G2}(t)\frac{A_s}{A_A}$ $P_N(t) = 1-(P_W + P_R = P_{G1}(t) + P_{G2}(t)$	At each iteration, no of probabilities P_N,P_W encountering a wall. PR encountering robot, P_S finding a stick, P_{G1}, and P_{G2} holding stick and another robot respectively. A_W surrounding wall, A_A whole arena A_R one robot.

3. Hardware Configuration features

Swarm robots' hardware is made in such a way to works with flexibility, scalability and robustness. Robustness is how they cope well even when a constituent robot fail to continue its mission while performing the task. The loss of individual do not leads to the failure of the whole system and is enabled by a highly redundant fault tolerance system whereas local sensing and communication enables the scalability, provided the removal of individuals from the swarm group do not results in a dramatic size reduction. Finally, the flexibility is achieved by their self-organizing and distribution capability. In this section, hardware architecture for different swarm robots are compared with respect to its sensory platform, actuation, locomotion, and controller which supports hardware architectural features like Self re-configurability and self-replication capability. Self-re-configurability and self-replication comes into account when there is necessity of flexibility, autonomy, and robustness [37]. Self-reconfigurable robot structures are classified into three categories like: lattice, chain and modular/ hybrid configuration system according to [38].They have showed wide capability of locomotion, self- assembly on different terrains [39]. Among the three, lattice configuration is much suited for dynamic environment since the units are connected in some regular space filling 3D patterns like cube, hexagon or any polygonal shape by which the control and motion are executed parallel. Whereas in chain configuration the motion control of each unit s executed sequentially on the configuration where the units are connected in a tree/ string topology. This configuration is more versatile because of the capability of self-reconfiguration without human intervention. Reconfigurable robot structures and their characteristics are discussed in [63]. Figure 2 shows some of the existing re-configurable, self-replicable swarm robots with multiple degrees of freedom (DOF). Among those MTRAN, ATRON and PolyBot shows a reptile, particularly a snake or a worm kind of a reconfigurable structure. There exist many snake robots as shown in Figure 3 which move like real snakes like weeko, Anna Konda, Uncle Sam, Omni Tread etc. While compared to these snake robots swarm shows only very limited capabilities due to its miniature size, lack of flexibility, limited hardware efficiencies which are not enough to meet the requirements to traverse in a constrained non laboratory conditions. More on the features on these robots are detailed in [69-74].

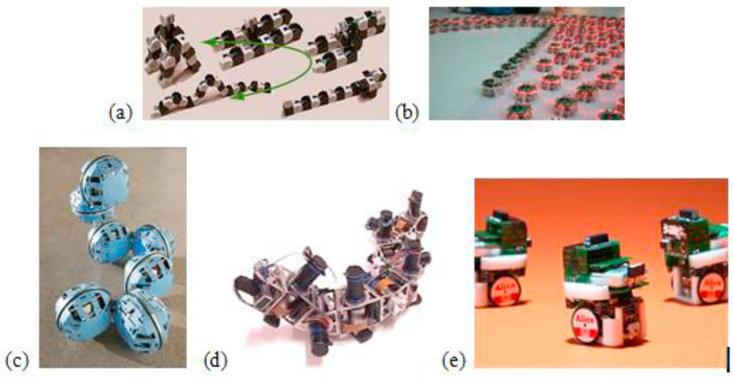

Fig. 2. Some of the existing swarm robots (a) M TRAN (hybrid structures, 2DOF) ; (b) e- puck (self replicable); (c) ATRON (lattice, 2DOF);(d) PolyBot (chain,2DOF) and (e) Alice (self replicable) respectively[47,48].

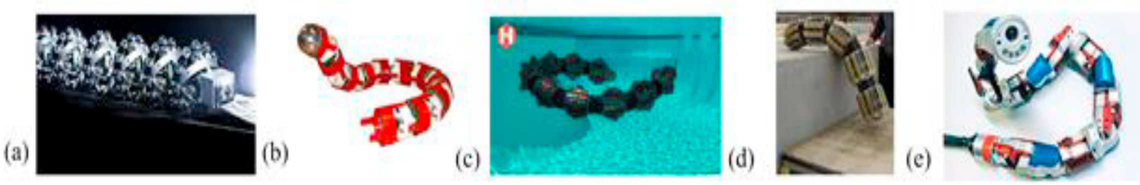

Fig. 3. Some of the existing snake robots (a) Weeko; (b) Anna Konda; (c) ACM 5; d) Omni Tread and (e) Uncle Sam [69-74].

Comparison of features of some selected swarm robotic platforms in terms of their configuration, degree of freedom, communication units and the controller used is discussed in Table. 2. The advantages and disadvantages of the same swarm robots are mentioned in Table 3. More on communication delay and packet loss analysis during multi robot localization is discusses in [66], and handoff in [67] respectively.

Table 2. Feature comparison of some selected swarm robotic systems [41-61].

Sl.no	Robot platform	Configuration	DOF	Communication	Controller
1	PolyBot	Chain	2	CAN bus standard	Motorola Power PC 555 embedded processor with 1 megabyte of external RAM
2	MTRAN	Hybrid	2	Relay PIC by serial communication	BASIC STAMP 2processor
3	ATRON	Lattice	2	IR communication	….
4	SamBot	Mobile	…	ZigBee wireless and CAN bus communication	ARM series STM32 microprocessor
5	S-Bot	Mobile	3	Wifi	14-PIC processors
6	CONRO	Lattice	4	IR transmitter and receiver form a local communication network	BASIC STAMP 2 processor
7	MiLyBots	Mobile (coordinated motion alone)	2	Communication between the central processing unit and each robot is facilitated by a Max-Stream wireless development kit connected to the central processing unit which communicates to each on board XBee OEM RF Module	8-bit ATmega 128 16MHz processor

Table 3. Advantages and disadvantages of existing swarm robotic platforms [41-61].

Sl.no.	Robot Platform	Pros	Cons
1	PolyBot	First self-reconfigurable most active module (each module of 5cm) connected system; Versatile Used Motorola PowerPC, 555 processor (external RAM of 1MByte) and brushless motor.	Inadequate sensory unit for mapping. Unable to work in unknown zones and rough terrain.
2	M-TRAN	Very compact modules; Extremely robust and reliable; Swift self-reconfiguration Multipurpose motion.	Connection mechanism works on an internally balanced weak magnetic force. Mapping and control complications. More Power consumption by motors
3	Sam-Bot	It’s a combination of mobile and chain-based modules and uses 4 docking mechanisms for connecting with other Sam-Bots. SamBot senses other bots using IR sensors.	IR sensors require line of sight between other bots, this limits the range. Lack of extra actuators, grippers, and sensors in the architecture for gathering information about the working environment.
4	ATRON	Each modules furnished with separate power supply, sensors and actuators. Each module is able to sense the state of its connectivity and relative motion	Since each modules includes 2-axis accelerometers only, a module cannot tell if it is turned upside down. It is very difficult for them to move themselves when two modules are connected. Their electronic performance is poor due to mechanical instability.
5	S-Bot	Capable of self-assembly and self-reconfiguration. Comprised of 2 to 40 S-bots, Fully autonomous with self-navigation and perception. Capable of communicating other S-Bots and transporting of heavy objects over very rough terrain.	The way for communicating with other S-Bots are only sounds and images. Consumes much power, operating time and reduces functionality due to large number of sensors and actuators.
6	CONRO	Small, rectangular, self-reconfigurable swarm robot with a low price; Versatile.	Onboard low-capacity batteries that limit the usefulness of modules. Limited sensors limit ability to sense surroundings. Only two controllable degrees of freedom.

4. Summary

A comprehensive survey on the swarm robot design, analysis methods and hardware architecture is studied. Based on the survey, the following points are summarized,

- Being a pure physics based design method, the entire sensory input space can be translated easily to the actuators output space using mathematical rules and the obtained behaviors can be combined using vector operators.
- The challenges in special credit assignment like huge size of the state space and incomplete perception of the environment make one of the automatic design methods, reinforcement learning difficult to implement.
- The computational intensity shows the draw in evolutionary robotics.
- Microscopic, macroscopic real robot analysis gains the attention to real time applications. Especially, when testing the robustness of the system or module under noisy environment, sensors and actuators. They can discriminate between realizable collective behaviors in practice and those that work only under unrealistic environment.
- In spite of potentials in scalability, robustness and flexibility, swarm robots are still lack of better performance in the real world environment due to hardware limitations.
- Mostly swarm robots have modules with exposed electronic components which only allow them to move in clean lab environments.

Further, this study can be extended for the development swarm robots and implement them to rescue operation, border surveillance, oil spill checking and many other applications etc.

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