A Review of Research in Multi-Robot Systems

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***Abstract*— Formally, a collection of two or more autonomous mobile robots working together are termed as teams or societies of mobile robots. In multi robot systems simple robots are allowed to coordinate with each other to achieve some well defined goals. In these kinds of systems robots are far less capable as an entity, but the real power lies in cooperation of multiple robots. The simplicity of multi-robots have produced a potentially wide set of applications such as military missions (battlefield surveillance), searching for survivors in disaster hit areas, parallel and simultaneous transportation of vehicles, and delivery of payloads. Although the research on multi-robot systems has attracted considerable attention worldwide in the past decade, the research in this area is still in its infancy. This paper surveys various interaction techniques in multi robot systems which are important with respect to goal attainment and task completion.**

Keywords – Multi Robot Systems, Coordination and Control, Communication, Localization and Mapping, Architecture of Multi-Robotic Systems

I. INTRODUCTION

It has been observed in many instances that multiple robots cooperate to perform complex tasks that would otherwise be impossible for one single powerful robot to accomplish. The fundamental theory behind multi-agent robotics suggests dispatching smaller sub-problems to individual robots in a group and allowing them to interact with each other to find solutions to complex problems. Simple robots can be built and made to cooperate with each other to achieve complex behaviors. It has been observed that multi-robot systems (MRS) are very cost effective as compared to building a single costly robot with all the capabilities. As these systems are usually decentralized, distributed and inherently redundant, they are fault tolerant and improve the reliability and robustness of the system. The simplicity of multi-robots systems has produced a potentially wide set of applications. However this simplicity also puts additional burden in setting up or deploying such systems as they can crash with higher probability during cooperation essentially in harsh conditions. The rest of this paper is divided into four sections. Section-II emphasizes upon various coordination and control techniques especially when robots interact with each other to move in a formation while preserving that formation like a flock of birds or insects. Several coordination and control algorithms suggested for robot flocking have been discussed. Section-III explores communication requirements of MRS i.e., explicit direct and implicit/indirect. Different approaches to multi-robot localization and mapping are discussed in Section IV. The environment in which multi-agent robots coordinate, and the accuracy by which robots can model the environment, can improve or degrade the performance of robot teams. Mapping the environment through the data received from robot sensors and creating a spatial model of the environment is a hot area of research in MRS. Finding the absolute or approximate location of self or a fellow robot in the spatial model is known as localization. Dynamic environments require simultaneous mapping and localization for both individuals and the group. This is known as Simultaneous mapping and localization (SLAM). SLAM techniques work well in cases where MRS lacks GPS support. The paper concludes with a few remarks on the current research directions in multi-robot systems.

II. COORDINATION AND CONTROL TECHNIQUES

One of the most important forms of coordination in multi-robot systems is observed when robots interact with each other to move in a formation while preserving the formation, like a flock of birds. Flocking [1, 2] is a form of collective behavior of large number of interacting agents with a common group objective. The engineering applications of flocking include parallel and simultaneous transportation of vehicles, delivery of payloads, performing military missions such as battlefield surveillance etc.

In 1986, Reynolds [3] introduced three heuristic rules that led to the creation of the first computer animation of flocking. He suggested the following three rules for a successful flock:

Flock Centering: attempt to stay close to nearby flock mates.

Obstacle Avoidance: avoid collisions with nearby flock mates.

Velocity Matching: attempt to match velocity with nearby flock mates.

These rules are also known as cohesion, separation, and alignment rules in the literature. These rules had very broad interpretations and the issue of how to interpret them correctly could only be resolved when Reynold published more recent papers, [4] which describe steering behaviors of autonomous characters in computer animation and [5] that describe method for constructing large groups of autonomous characters. These autonomous characters were then made to respond in real time to interact with the user, as well as with other characters and their environment.

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Helbing et al. [6] studied the escape panic phenomenon in which a crowd that is trapped in a large building (or arena) attempts to evacuate that location in case of an emergency; this answer how do flocks perform split/rejoin maneuvers or pass through narrow spaces. Tanner et al. [7] proposed a centralized algorithm for a particle system but that leads to irregular collapse for generic initial states. They also proposed a distributed flocking algorithm by exploiting the properties of algebraic connectivity of graphs in interconnected switched networks and this leads to irregular fragmentation. Fragmentation and collapse are two well-known pitfalls of flocking. Mesbahi [8, 9] emphasized the role of state-dependent graphs in information networks. He suggested that in order to control the network information it becomes important to control the network itself. Interestingly dynamic flocks turn out to be examples of state dependent graphs. Centralized algorithms for flocking are neither scalable in terms of computational nor communication costs. The work by Chang et al. [11] uses gyroscopic forces for collision avoidance. They introduced decentralized control law that constituents of a group of vehicles can follow to accomplish some specified control objective while avoiding collision with one another and with unforeseen obstacles. A distributed technique with cooperative leader-follower approach is introduced by Carpin and Parker [12] to coordinate the team level and robot level behavior. They also implemented a multithreaded framework that could handle a heterogeneous multi-robot system which uses different types of sensors for communication. Parker et al. [13] extended [12] and introduced a leader with the rich sensing capability as the central figure of a robot team tightly coupled with simple follower robots to assist them in navigation. The follower robots have no on-board capabilities for obstacle avoidance or localization and have minimal capabilities for kin recognition. This kind of centralization in multi-robot systems makes the robot leader more costly thus making the system less robust (single point of failure). Eervai and Prencipe [14] provided a formal definition for the flocking problem based on a leader-followers approach. They addressed flocking from computational viewpoint and proposed a flocking algorithm that applies to formations that are symmetric with respect to the movement of the leader without an agreement on a common coordinate system (except the unit distance). They took an additional assumption about the speed of the robots. However their algorithm requires election of the leader from the follower robots. Yosuke Hanada et al. [15], proposed a novel flocking strategy based on the leaderless approach where a specific robot is not assigned to conduct its swarm. Based on local interactions they enabled a large scale swarm of robots to navigate autonomously in an environment which is populated with obstacles. Canepa et al. [16] proposed an architecture where a leader is not known a priori. This approach is asynchronous and robots are oblivious in the beginning, the robot leader is elected by using a probabilistic algorithm after which, the robots position themselves according to a specific formation and finally, the formation moves ahead. The limitation of this architecture is that it only lets the formation move in a straight direction. The second limitation to their approach is that the leader once elected cannot change. This is a severe limitation of their architecture in the event of failure and/or in the presence of faulty robots. Gianluca Antonelli et al. [17] considered a widely used approach of Null-space-based behavioral control. In this approach the flocking is pursued in a decentralized manner. The robots are arranged in priority and since the elementary behavior of each robot is already defined they only require local information concerning their neighbors. Flocking in the presence of a static or moving rendezvous point has been discussed and verified by numerical solutions. Mao Yang et al. [18] suggested a distributed co-adaptive control algorithm and they proved that all swarm members can converge to a common velocity only by means of local information. Li Xiang et al. [19] present a decentralized control algorithm for a swarm of robots based on geometric approach. They developed a control algorithm, which was executed by all members of a swarm to achieve collective behavior.

Since most of the applications of swarm robotics require cheap robots to work in hazardous environments (military missions like battlefield surveillance, tracing for survivors in disaster hit areas) the research on fault tolerant nature of these systems requires substantial investigation. In the past decade only few works discussed fault tolerance in the flocking of mobile robots. Some robots might crash or fail while flocking. It is necessary to find a method that can distinguish the working robots in waiting state from the crashed ones. Samia Souissi et al. [20] developed an algorithm which ensures that the crash of faulty robots doesn't bring the robot formation to a permanent stop. Their algorithm relies on a k-bounded asynchronous scheduler such that the beginning and end activations across robots are not synchronized. Appropriate restrictions were applied to the movement of robots to agree on common ranking policy. Based on k-bounded scheduler and common ranking the robots can eventually detect crashed robots, and thus trigger reorganization of the formation. Robots flock by following simple rules governing their movement. Yoshida et al. [21] proposed a fault tolerant algorithm to select the active mobile robots from a group of mobile robots. Unfortunately, the authors only considered initial crash faults of robots, i.e., a faulty robot, which makes no motion from the beginning of execution of the algorithm. Ali E. Turgat et al. [22] studied self organized flocking in a swarm of mobile robots; they allow the robot to sense the orientation of neighboring robots. Performances of flocking with the help of matrices like order and entropy have been evaluated. Michael Rubenstein and Wei-Min Shen [23] give a scalable and distributed model for self organizing and self healing. Their work is inspired by the nature of natural organisms of self healing/forming.

III. COMMUNICATION

Robots in MARS are simple and have limited communication capabilities. This limit on the communication bandwidth in MARS has created debate on the level of communication that should be allowed in MARS. The distinction between implicit/explicit communications in literature is clearly visible.

Implicit communication sometimes also called stigmergy is predominant in social insects (e.g., the pheromone trails in ants). Implicit communication is a method of communicating through the environment. On the other hand explicit communication can also be observed (e.g., the waggle dance of honey bee workers).

Coordination doesn't necessarily require centralized control by means of a leader. Pheromone based communication is a type of implicit communication. There are many research works that have explored the use of pheromone signals to convey messages within the robots in the swarm [32, 33, 34]. A higher level of pheromone called "virtual pheromone" was introduced in [35, 36] to employ simple communication and coordination to achieve large scale results in the areas of surveillance, reconnaissance, hazard detection, and path finding. Explicit communication is a beneficial technique and can be applied when the number of agents is less and when a fast reaction is expected, for instance when a danger is detected and countermeasures are to be taken. Vito Trianni et al. [31] make a group of swarm robots flock in an arena which contains holes and used explicit communication to avoid the robots from falling into the holes. Their work could not address how a group of robots can avoid obstacles as a whole. McPartland et al. [37] made a comparison between implicit and explicit communications theory by applying it to two different swarms of robot which are assigned to explore a given environment in the shortest period of time. Paul et al. [38] introduced and explored simple communication strategies which implemented implicit and explicit communication.

The communication between robots can multiply their capabilities and increase the efficiency. Even though there is no clear conclusion on what type of communication is better for robot swarms, but most of the current research is aiming towards implicit communication for its robust characteristics.

IV. MAPPING AND LOCALIZATION

For a robot to navigate its environment, map building of its environment is always the fundamental job that it has to do. The term mapping is usually talked about when the environment of the robot is unknown. The robot tries to discover and create a spatial model of its environment. In multi-robot systems the accuracy by which robots can model their environment has a deep impact on the performance of individual and on team performance, such that it would take longer time for convergence and in turn in formation of a flock pattern. Having created the spatial model of its environment, in multi-robot systems the robots try to estimate the absolute or approximate coordinates of self and fellow robots in the environment. Finding the absolute or approximate location of self is known as localization, and that of fellow robots is known as kin recognition.

Concurrently building up the map of the environment and using this map to obtain the estimation of the location of the robot is the central problem that is focused by simultaneous mapping and localization [39, 40]. The problem of simultaneous mapping and localization is a difficult problem primarily because of two reasons: first the environment is unknown and is inherently unpredictable and second due to noise in the sensor measurement which severely limits the accuracy by which robots can map their environment. Multi-robot systems prove to be faster and more accurate when it comes to mapping of the environment [41]. The parallel exploration of the environment finishes the mapping of environment in much less time as compared to a single robot doing the same thing. More accurate results can be drawn by merging overlapping information received from different robots.

With the centralized approach the information from all robots is required to construct the map [42, 43, 44] and with the decentralized approach the sub-map building process of one robot is independent from other robots [40, 45, 46]. The sub-maps are fused into a global map periodically. The biggest problem with the centralized approach is that if one robot and/or the centralized node that is responsible for creating the map fail, the entire system halts although other robots are in healthy condition. In contrast to this the decentralized system is more robust and fault tolerant since the robots are just required to provide the local sub-map when necessary. Failure of one robot would not affect the map creation process.

V. ARCHITECTURE OF MRS

Multi-robot systems can produce a wide range of organized and coordinated behaviors by utilizing the influence of the environment. When designing a multi-robot system various aspects must be considered: the group architecture [24], whether the system's control is centralized or decentralized; the ability of one robot to recognize and model other robots [25], also known as kin recognition; and the communication structure [26]. The group architecture, upon which the collective behaviors are implemented, determines the capabilities and the limitations of the system. Group architecture can be centralized or decentralized. In a centralized architecture a single agent gives order to the other agents and supervises the correct performance of a cooperative task. This kind of architecture can be highly efficient when it comes to controlling a small group of robots. An example of centralized architecture is [27]. In this group architecture a computer with a sophisticated vision system senses all the robot positions, performs the task allocation and controls each robot. However the control of each member of the system by an external controller is difficult or impossible as the colony grows in size [26]. On the other hand decentralized architectures, inspired by insect societies, do not have an agent that controls the whole system and are a generalization of behavior based control over multiple robots [26]. Decentralized architecture can be fully distributed in which all agents are equal with respect to control, or hierarchical, in which they are locally centralized. Few examples of decentralized architectures are [28, 29, 30]. Regarding the ability of a given robot to recognize and model other robots [29] if an agent can model the intentions, beliefs, actions, capabilities and states of other agents, this can lead to more effective cooperation between robots. Few more examples of robot architecture include [47], which tends to use traditional AI techniques and is developed to resolve problems in a distributed manner for multi-robots in internal environments. An example of behavior based architecture for a team of mobile robots is [50], this architecture is designed to model the robot's behavior so that it can select a reactive low level for its survival, to plan high level objectives oriented to a sequence of behaviors, to carry out spatial and topological navigation, and to plan cooperative behaviors with other robots. A distributed system of robots made up of a great number of autonomous robots [49], has been designed for multiple non-intelligent robots to exhibit a collective intelligent behavior. The interaction in such architectures is limited to nearest neighbors. Finally, one most widely used simulation software used nowadays for programming multi-robot applications is [48], it employs one-to-many client/server style architecture where one server serves all the clients of a robot device and it relies on a TCP based protocol to handle communication between client and server.

VI. CONCLUSION

Multi-robot systems as a means of solving complex problems in different domains have received considerable attention by the researchers in past two decades. Inspired from the innate behavior of cooperation of small living organisms like ants, birds, and fishes, people have been trying to bring out the same level of intelligence in multi-robot systems which is visible from the cooperation of living organisms. Several coordination algorithms have been proposed, these algorithms are broadly divided into leaderless approaches and leader follower approaches. It is seen that leader less approaches are more feasible when it comes to cooperation among a large number of oblivious, autonomous, and identical robots, as they don't make the leader burdened with the responsibilities of channelizing coordination in a group. From a communication perspective also there is a debate in the research community worldwide on the level of communication among individual robots in a multi-robot system. Explicit communication is suitable in a situation where immediate reaction is required, for example, collision avoidance, obstacle detection etc. Implicit communication is suitable in a situation where real time response is not required, for example path planning, pattern formation etc. Hybrid approaches have been developed which considers both implicit and explicit communication into account. For a robot to navigate its environment it should be able to know/understand its environment. In an unknown environment robots have to map the environment and then they do a localization of self and their peers, there are methods using which robots do localization and mapping simultaneously (SLAM). Parallel SLAM by a group of robots speeds up the process. Each robot, independent of each other, creates the sub-map and then periodically fuses their maps to create a global map of the environment. The group architecture of the multi-robot systems is of high importance. It is basically decided by seeing the application where multi-robot robot systems are required to be deployed. If the application has real-time needs/demands then the centralized architectures are preferred otherwise decentralized architecture.

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