Chapter 1

Introduction

Swarm robotics is a relatively new field of study that has in recent years attracted the interest of researchers in academia and industry. The interest is primarily fueled by the development and effectiveness of specialized Multi-Robot Systems (MRS) in accomplishing complex tasks and availability of multi-robot simulators [1, 2]. A multi-robot system, in general, can be described as a “set of robots operating in the same environment to accomplish the system goals”. Even if a single robot can complete a given task, the possibility of deploying a team of robots can improve the performance of the overall system. In an MRS, instead of utilizing a single powerful robot to execute a complex task, the task is decomposed into subtasks which are executed by a team of robots under a centralized or decentralized control. In a centralized multi-robot system, the global information about the state of the system is maintained and controlled by a central entity. Centralized MRS are suited for systems with a limited number of robots that operate in known and unchanging surroundings. In decentralized MRS, each robot can function as an autonomous unit which adapts its functionality in accordance with the state of its surroundings. The robots in MRS are fairly complex, equipped with powerful computational units, a large amount of memory, sophisticated sensors and actuators. These robots can be utilized to mitigate human effort, increase productivity, provide a safe working environment, improve the quality of life or at times even save human lives. While centralized multi-robot systems have been utilized in several applications, such as vehicular assembly lines, warehouse transportation, etc., decentralized multi-robot systems have been employed in applications such as mapping of urban areas, search and rescue operations, etc [3–5]. The field of cooperation and coordination of multi-robot systems, focussed on developing cost-effective decentralized MRS to improve the quality of life of human beings have been a subject of considerable research efforts in the last few years.

Swarm robotics is an approach to coordinated multi-robot systems that are inspired by the self-organized behaviours of social organisms found in nature [6]. The collective swarm behaviours such as the foraging of ants, the wasp's nest building or construction of the termite mound were considered for a long time as the mysterious aspects of nature. Researchers have demonstrated that members of swarm do not require detailed knowledge/representation of the environment or information about other members of swarm to exhibit such complex behaviours [7]. The members of swarm found in nature communicate via a phenomenon referred to as stigmergy, i.e. communication by means of changing the environment [7]. During a foraging task, ants communicate with each other by leaving a pheromone trail (changing the environment), thus marking the shortest route identified by it towards the source of food [8]. Trails are followed by more ants, reinforcing the better routes and thus gradually identifying the best path. The intelligent group behaviours which emerge from a group of individuals with poor abilities, through local communication and information sharing, enable the members of a swarm to accomplish complex tasks. This kind of intelligence, called as " swarm intelligence" is found in the nest construction of termites, foraging of ants, etc. Though the members of these swarms found in nature are incapable of completing the task individually, a swarm can accomplish the task easily through local communication and cooperation.

Swarm robotics address the design and implementation of robotic systems composed of swarm of robots which interact and cooperate to achieve their goals. Swarm Robotic Systems (SRS) and MRS are examples of collective robotics, in which team of robots collectively solve a problem. SRS utilize decentralized, cooperative, cost-effective simple robots. When compared to MRS systems, robots in SRS can utilize local interactions among each other to produce complex and emergent behaviours which are beyond the capabilities of individual robots. Robots in a swarm may aggregate together to form suitable patterns or formations to perform tasks. Swarm robotics has now become an interdisciplinary frontier and can be considered as an instance of collective robotics which addresses mobility, flexibility, and robustness in a novel way, combining different aspects such as distributed control, local interaction, self-assembling mechanisms, and collective behaviour [9].

1.1 Comparison of Multi-Robot Systems and Swarm Robotic Systems

Brambilla et al. define an SRS system as "A system which consists of autonomous robots with local sensing and communication capabilities, lacking centralized control or access to global information, situated in a possibly unknown environment performing a collective action" [10]. Iocchi et al. have proposed a taxonomy for cooperative robots which may be utilized to distinguish swarm robotic systems from other collective robot systems [1]. The taxonomy is structured in different levels as shown in Figure 1.1. The first level, i.e "Co-operation" is concerned with the ability of the robots in the system to cooperate with each other in order to accomplish a specific task. A co-operative system, as the name suggests, is composed of “robots that cooperate to perform a global task”. Robots in MRS generally exhibit only minimal cooperation among each other whereas the individual robots in SRS exhibit higher degree of co-operation to achieve the goal. The second level of taxonomy is concerned with the "knowledge" that each robot in the system has about each other. "Aware" robots act, based on knowledge or information from their team members, while "Unaware" robots act without any knowledge or information about other robots

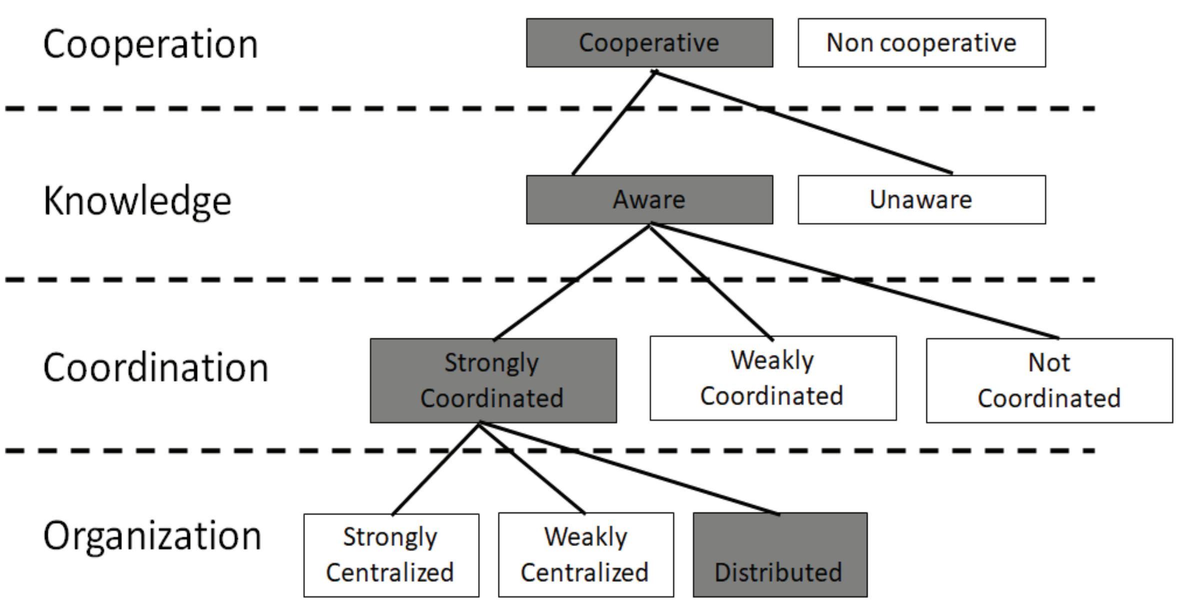

Figure 1.1. Taxonomy proposed by Iocchi et al. to represent different types of collective robots [1]

in the system. It may be noted that the notion of knowledge is not equivalent to communication, i.e using a communication mechanism does not entail awareness and vice versa. Robots can be aware even if there is no direct communication between the robots. MRS, as well as SRS, are aware systems although the degree of awareness is higher for SRS. The third level is concerned with the mechanisms used for coordination. "Coordination" is defined as the “cooperation in which the actions performed by each robot takes into account the actions performed by the other robots in such a way that the whole ends up being a coherent and high-performance operation”. The underlying feature of coordination is the coordination protocol which defines the set of rules that the robots must follow in order to interact with each other in the environment. Therefore, the coordination level can be further classified based on the type of coordination protocol. MRS are mostly weakly or not coordinated while SRS are capable of working in strongly coordinated manner, even though they may choose to work in a weakly coordinated manner as well. The fourth level of the taxonomy is concerned with the way the decision system is realized within the system. SRS are decentralized or distributed in control, whereas MRS are mostly strongly centralized or weakly centralized. According to this taxonomy, SRS are cooperative, aware, strongly/weakly coordinated and distributed as highlighted in Figure 1.1.
The major characteristics of swarm robotic systems which differentiate them from other collective robot systems are identified by Navarro et al. [6] as follows.

- Robots in a swarm are typically low cost, physically simple robots which can collaborate in order to improve its performance or to accomplish complex tasks which are beyond their individual capabilities.
- Robots in a swarm must be autonomous, i.e a robot should be able to sense, navigate and operate in a dynamic environment on their own by making appropriate decisions.
- Robots in a swarm must be mostly homogeneous. Although groups of different types of robots may be present in the swarm, these groups must not be too many.
- Although it is not mandatory that there should be a large number of robots in a swarm robotic system, the control rules, algorithms and control strategies utilized should be scalable.
- Robots in a swarm need not have access to global knowledge about the environment nor are centrally controlled. The coordination of swarm is distributed in nature.

- Robots in a swarm can have only local communication and sensing capabilities. Nevertheless, certain global communications are acceptable, such as global communications for updating the control strategies of the robot, system initialization or for sending terminal signals.

Effective solutions for implementing stigmergy observed in swarms found in nature are not yet available for swarms of robots. The most common technologies for inter-robot communication in a swarm are Infrared, Bluetooth, Wireless LAN or other wireless technologies as is utilized in Mobile Wireless Sensor Networks (MWSNs)[11]. The nodes in MWSNs combine sensing, computation, and communication into a single device and are typically constrained in terms of energy, memory and processing capabilities. The main goal of MWSNs is to reliably detect events and respond to them using collective information provided by sensor nodes. Interestingly, SRS and MWSNs share several common characteristics such as the use of a large number of robots/nodes, limited individual capabilities of robots/nodes, co-operative behaviour among nodes, etc as indicated in Table 1.1. Both domains can operate complementarily to each other such that the swarm robots can utilize the wireless network for communication and co-operative behaviour, while MWSN can take advantage of the mobility provided by swarm robots to improve its sensing range - thus forming a self-healing network. Although static WSNs are successfully deployed in several applications like precision agriculture [12], monitoring of oil and gas pipelines, [13], etc. the development of MWSNs is still in its nascent stages. The work presented in this thesis is specific to SRS and MRS systems which utilize wireless networks for inter-robot communication.
As discussed in this section, it can be understood that SRS system is expected to exhibit a higher degree of cooperation, awareness, coordination and decentralization when compared to MRS. For certain applications (e.g warehouse transportation, ambient assisted living systems, etc.), incorporation of the characteristics of SRS such as the decentralized control and cooperative behaviour in MRS will bring down the cost of the system while increasing the productivity. The work presented in this thesis can be utilized for SRS and low-cost MRS. [14, 15].

1.2 Advantages of Swarm Robotic Systems

The major advantages of SRS, when compared to utilizing a single robot or MRS in accomplishing a complex task, are summarized in this section.

- **Distributed Action:** The group of robots in SRS and MRS can operate simultaneously at different places. SRS is especially suitable for tasks which are spread over a vast area. If the task can be decomposed into sub-tasks, then parallelism can be exploited among robots and the sub-tasks can be performed more efficiently and quickly when compared to a simple robot [16].

- **Scalability:** Members of the swarm utilize only local interactions and the control strategies utilized in SRS are distributed in nature. Owing to this, the robots can join or quit the SRS at any time without interrupting the whole swarm, thus forming a scalable system. SRS are designed to be adaptable for different sizes of population.

- **Adaptability:** Members of swarm can autonomously change their behaviour in the population through cooperation and suitable task reallocation schemes without any external control.

- **Fault Tolerance:** In SRS, a group of cooperative robots are utilized. Hence, even if a few robots in the system fail, the swarm can still work towards completion of the task, although the performance of swarm may degrade inevitably with fewer robots. Thus, single point of failure can be avoided and this characteristic is especially useful when robots are to be deployed for missions which are prone to damage to robots such as detection of landmines, search and rescue operations, etc.

- **Energy Efficiency:** Since the individuals in a swarm are smaller and simpler, their energy consumption is much lesser when compared to the complex robots typically found in MRS.

Table 1.1. Comparison of SRS, MRS, MWSN

	Swarm Robotic Systems	**Multi-Robot Systems**	**Mobile Wireless Sensor Network**
Population size	Highly variable	Small	Variable
Control	Decentralized, autonomous	Mostly Centralized/ remote	Decentralized Centralized
Homogeneity	Homogenous	Heterogenous	Mostly Homogenous
Structural Flexibility	High	Low	Low
Scalability	High	Low	Medium
Mobile	Yes	Yes	Yes

In applications which do not support recharging facilities or when systems are required to be battery operated for longer durations of time, the swarm robots can extend the lifetime of the system. However, the inter-robot communication mechanisms should also be optimized for energy efficiency.

- **System Cost:** In SRS several low-cost, simple robots are utilized. The individuals in the swarm can be massively produced while single robot requires precision machining. The design, manufacturing and maintenance cost of swarm robotics is significantly low. The whole system will be cheaper than a complex single robot even though the number of robots in the swarm can be huge even in the order of hundreds.

  Swarm robotics thus integrates the potential advantages of distributed computing such as fault tolerance, adaptability, robustness and scalability in the field of robotics. In-addition to improving the performance of the system when compared to a single robot system, decentralized MRS also brings in adaptivity and fault tolerance into the system. Decentralized MRS can autonomously modify its own behaviour, depending on changes in the environment or changes in the system requirement, such that the performance of the entire system can be improved. Thus decentralized MRS can also deal with individual robot failures efficiently without leading to a system failure.

1.3 Potential Applications of SRS and MRS

A few potential applications of MRS and SRS are described in this section. These potential applications of SRS and MRS also serve as the motivation for further research in the development of SRS and MRS. Swarm robots, in particular, are ideal candidates for applications or tasks with the following characteristics [17].

- Tasks which require coverage of large areas
- Tasks which are to be performed in hazardous conditions or for applications which are prone to loss of robots
- Tasks which requires scaling population of robots

- Tasks which require redundancy, or tasks in which multiple robots are required to perform the same task

A few application domains which will significantly benefit from the utilization SRS are described below.

- **Warehouse Transportation:** The utilization of swarm robots can transform the warehouse industry drastically. For example, the Kiva robots used by Amazon in their warehouse for transportation of goods, navigate by scanning and following a set of bar codes on the floor [18]. More flexibility in the movement and hence increase in productivity can be achieved by if robots can locate their position in the field of deployment [19]. The researchers at 'Fraunhofer Institute for Material Flow and Logistics' are working on making warehouse robots smarter and more efficient by allowing them to communicate and cooperate like a swarm of ants [20]. Instead of having a central computer to control the movements of every robot (as with Kiva), Fraunhofer propose to utilize a swarm of robot, that are autonomous and can cooperatively decide on which of them should go where and perform which function.

- **Healthcare and Ambient Assisted Living Systems (AALS):** Swarm of robots can navigate through hospital hallways- transporting medicines, medical supplies, etc. from one point to another, thus reducing the effort of medical practitioners and support staff. According to National Centre for Health Professions Education (NHCPE), the elderly population in India will increase to 12% of the national population by 2025. Hence it is necessary to provide preventive, curative, and rehabilitative care to the elderly population. Systems for enabling independent living by the elderly such as the AALS is essential to enhance the quality of life in a cost-effective manner. The swarm of robots can be used in geriatric care systems to enhance health and psychological well-being of elderly users by providing companionship [21]. These robots can locate the elderly, navigate towards the elderly and function as companions to them. Robots with telepresence support can also be utilized to assist the elderly to communicate with a remote medical practitioner or a relative in case of emergency [22].

- **Search and Rescue:** Search and rescue missions require a population of robots to scale according to the requirements. For e.g. in case of a disaster, initially a few robots may initiate the search and rescue operation and more robots may be inducted into the system based on their availability. Stormont et al. have elaborated on the potential of using a swarm of autonomous robots to react to a disaster as first responders [23]. The robots can search for survivors and provide suitable information for defence or other personnel to perform search and rescue, till the area is safe for human beings to enter. In these kinds of applications the workload may change with time and hence scalable and cost-effective networks such as SRS are ideal choice for these applications. Researchers have developed SRS using robots named as ‘s-bots’ and demonstrated self-assembly of robots to form a chain-like structure. Through the formation of suitable structures, the proof of concept of utilization ‘s-bots’ in a rescue mission was demonstrated by pulling an object from one point to another on the floor [9]. These kind of behaviours are beneficial in search and rescue missions. For example, in an SRS, a complex object may be transported by a group of small, simple robots by forming suitable formations or a set of tiny wheeled robots can cross a trench by forming a chained structure [24].

- **Defence Services:** Modern military forces operate as a network, with networked human-inhabited platforms in land or air for operations such as surveillance, search and rescue or warfare. The military is constantly searching for methods to improve their soldiers' capabilities in the field but more importantly, they are trying to develop devices that will allow them to perform tasks without endangering the lives of soldiers. Swarm of robots in land or air can be programmed to form vast networks. The swarm could be dropped by Unmanned Aerial Vehicles (UAVs) and released into the target location to perform tasks like reconnaissance, physical attacks on military bases, mine detection, etc [25]. Benefits of deploying human-inhibited intelligent platforms in hostile situations like landmine detection, disaster recovery, etc. are recognised by defence forces all over the world. However, the widespread deployment of robots as human substitutes in risk-prone, unmapped or dynamic terrains is challenging and a dream yet to be true. In certain applications, the robots may not be retrievable after the task and use of complex and expensive robots are thus economically unacceptable. Since the robots in a swarm are cost-effective, they can be utilized in applications like mine detection, which are prone to damage of robots.

- **Precision Agriculture:** Robotics is expected to provide assistance in improving the crop productivity and reducing production cost in the large-scale agricultural applications and precision farming. The European Coordination Hub for Open Robotics Development (ECHORD) offers research consortia funding for developing robotics solutions for real-life problems. Swarm Robotics for Agricultural Applications monitoring (SAGA) is a collaborative research project funded by the ECHORD, which targets the development of decentralized monitoring/mapping of agricultural fields and the detection and mapping of weeds [26]. Swarm of robots can also be used to guard the agricultural field or monitor indoor and outdoor greenhouses, or perform periodic or event based treatment of the field, thus reducing the human effort at the same time increasing the productivity of the crops.

1.4 Factors Affecting Widespread Swarming

Swarm robotics, as a discipline, has attracted a significant number of research groups currently contributing to the field. Despite their potential benefits swarm robotic systems are not yet widely utilized for real-world applications and are still confined to the world of academic research. The major technological factors holding back swarming include, but are not limited to, are identified as follows:

- **Lack of Robust Communication Techniques:** Swarms found in nature communicate via stigmergy, i.e. they communicate via the environment or by changing the environment based on requirement. Creating an artificial pheromone is nearly impossible for any of the practical applications. Common methods of communication proposed for communication among members of the swarm are Infrared (IR), Bluetooth, Wireless LAN, or other wireless technologies as utilized in MWSNs or Wireless Sensor Networks (WSNs) [27]. Inter-robotic communication requirements widely differ in most robotic swarms, depending on factors such as the deployment location, the size of the robots, available budget and communication range. However, the real-time wireless control, cooperative data collection and navigation, task allocation, and task migration in a distributed swarm robotic network is possible only if the robots are synchronized to a common notion of time. With the constraints such as limited communication bandwidth, limited battery power, limited processing power, dynamic topology, etc. time synchronization for a dynamic network like swarm robotic system is a challenging problem to solve. Although several works are reported in the field of routing and medium access control for mobile wireless sensor networks, or for navigation in a collaborative swarm, a prior time synchronization is stated as one of the assumptions when time dependency is involved. Hence, robust means of communication and synchronization among robots is critical in building swarm robotic applications [28].

- **Lack of robust Localization Schemes:** Localization is the process of determination of the position of an object in a two-dimensional or three-dimensional space [29]. Data collected from any distributed network has significance only when associated with a timestamp and a location stamp. Robots in MRS or SRS should have the ability to find their positions if they are to be employed for any real-world application. Development of localization schemes for Global Positioning System (GPS) denied environments especially in indoor environments is challenging as they are prone to high Non-Line-of-Sight (NLOS) and multipath effects due to the influence of obstacles like walls, equipment, movement of human beings, etc. Swarm robots can co-operatively aggregate together to perform tasks. Localization is also required for the formation control and cooperative task completion. Hence the expected accuracy of localization is in the order of centimetres. Implementing cost-effective localization scheme still continues to remain as a challenge in robotic systems. For an SRS localization technique or algorithm should scale well with the size of the network [30].

- **Availability of Cost-effective Robots:** Swarm robotics or robotics, in general, is a multi-disciplinary field and their development requires knowledge in kinematic modelling of robots, electronic hardware, electronic instrumentation, networking, communication systems, artificial intelligence and so on. Optimizing one aspect of design may be possible only with the trade-off of one or more of other factors. Most often researchers end up customizing existing robotic structures and augmenting the required features based on application. The cost of customization to integrate into a fully functional robot may be very costly or may suffer performance degradation as these parts are typically not created for robots, but are adapted from other types of application. Researchers who have access to multiple units of existing autonomous robotic platforms including commercial ones and seeking to study swarming have currently no other option than devising their own software or network stack due to lack of availability of standardized hardware or software stack leading to the huge development time. Hence only small groups of robots have been presented in most of the swarm robotics literature and still, most of the work is limited to simulation-based study.

- **Lack of Appropriate Task Allocation Schemes:** Another factor preventing widespread use of SRS is the lack of algorithms for implementation of coordinated control of swarm. Making a single, mobile, autonomous robot working in a reliable and fault tolerant manner is a challenge, and is even more so for a robotic swarm. Distributing and scheduling a set of tasks among a group of robots in a dynamic environment, to achieve certain system goals taking into account the operational constraints is referred to as task allocation [31]. The complexity of task allocation increases with the size of the swarm and heterogeneity among the members of the swarm. Task allocation is an open problem of research in multi-robotic systems and in existing solutions very less focus has been given to the inter-robot communication aspects of the task allocation problem.

1.5 Scope and Objectives of Research Work

This thesis proposes solutions for three fundamental issues in swarm robotic and low-cost multi-robot systems i.e. the time-synchronization, localization and task allocation. In this thesis, in addition to robots in SRS, cooperative robots in low-cost MRS systems are also referred as swarm of robots. The objectives of the thesis study are as follows:

Objective 1: To design, implement and validate a scalable, topology independent, energy efficient, global time synchronization framework for swarm of robots.
The objective 1 was achieved by designing a novel time synchronization framework, to cater to the above-mentioned requirements. The framework is referred to in this thesis as "Swarm-Sync". The major contribution of this work is in terms of proposing a scalable, topology independent, mobility-assisted time synchronization framework with resynchronization interval in order of several minutes (tested up to 10 minutes). The performance evaluation of framework was experimentally performed on robots in single-hop and multi-hop scenarios. Detailed analysis and performance comparison of the proposed framework with two major class of time synchronization protocols, i.e. the prediction based and consensus protocols are also presented. The framework can also provide a bounded synchronization error throughout the network.

Objective 2: To design a two-dimensional beacon based indoor localization scheme for robots, which is suitable for localization in Line-of-Sight (LOS) and Non-line-of-sight (NLOS) conditions.

To achieve the objective, an ultrasonic beacon based localization scheme is proposed. An ultrasonic transmitter and receiver hardware is designed and evaluated for accurate time of flight measurements. For a detailed analysis of the localization inaccuracies under NLOS conditions, Locusim- an room acoustic simulator was utilized. Design of an artificial neural network based location estimation unit is presented for accurate and reliable localization under LOS and NLOS conditions. The performance analysis of the location estimation unit for various NLOS and LOS scenarios simulated in Locusim simulator is also presented.

Objective 3: To design a two-dimensional short-term, self-localization scheme for robots in indoor environments.

A two-dimensional self-localization scheme using Inertial Measurement Unit (IMU) is proposed in the thesis for localization of robot for short distances. Self-localization scheme is proposed to enable the robots to perform cooperative task completion without depending only on beacon based localization. The self-localization scheme is required to perform continuous localization of the robot between the start and stop events of the robot. For performing activity detection, which is identified as a crucial step in localization, fuzzy inference system is proposed. The performance of the proposed scheme for short-term self-localization of a robot is evaluated for different test scenarios.

Objective 4: To design a distributed task allocation framework for swarm of robots which can be utilized to solve any of the eight different types of task allocation problem identified by Gerkey and Matarić. The task allocation scheme should be energy efficient and should be suited for both clustered and non-clustered deployment scenarios.

A novel, fully distributed, task allocation scheme which can be utilized to solve the 8 different types of task allocation problems identified by Gerkey and Matarić is proposed. The proposed task allocation scheme is simulated using Autonomous Robots Go Swarming (ARGoS) simulator. The feasibility of implementation of the proposed task allocation scheme for clustered and non-clustered environments is analyzed. The computational complexity and communication overhead of the task allocation scheme is also presented in the thesis.

1.6 Organization of the Thesis

The rest of the thesis is organized as follows. Chapter-2 presents a detailed literature review which leads to the identification of gaps in the research and the formulation of the core objectives of the research work. The chapter provides a comprehensive review of the current state-of-the-art techniques and technologies pertaining to different objectives identified in Section 1.5. A detailed review of the time synchronization protocols available in the literature is presented. This is followed by the review of the major techniques and technologies available for indoor localization. A comparative study of the accuracy achieved by the available localization techniques and their limitations are presented in this chapter. A brief review of the different self-localization schemes for robots in indoor environment is also presented. Chapter 2 also presents the literature review of the different solutions available for multi-robotic task allocation.

Chapter-3 presents the details of work carried out to accomplish the Objective 1. The chapter begins with the identification of the desired characteristics of a time synchronization protocol for a scalable networks such as a SRS or MRS. The key issues in the techniques utilized in time synchronization protocols available in the literature based on MAC level timestamping is discussed. A novel time synchronization framework, "Swarm-Sync", for swarm and multi-robotic systems is presented in the chapter. The hardware architecture of the robot which is developed and utilized for testing the framework is presented. A detailed account of the test setup and various test scenarios utilized for validating the proposed time synchronization framework in indoor and outdoor environments is presented in detail. The chapter also provides a detailed experimental analysis of different time synchronization protocols belonging to the two major class of time synchronization protocols, i.e. the prediction based and consensus protocols. The chapter concludes with the performance analysis of Swarm-Sync synchronization framework and compartive analysis of the proposed framework with the related work in literature.

Chapter-4 presents the details of work carried out to accomplish Objective 2. An ultrasonic transmitter and receiver system was designed, implemented and tested. With RF communication, ultrasound beacons and time offset compensation, an accurate method for recording the time of flight measurements between of target and beacon node was proposed. A two stage artificial neural network based location estimation unit (ANN-LEU) is proposed in this chapter which utilize the time of flight measurement from target nodes and beacon nodes to provide the (x,y) location estimation of the target. An optimal neural network architecture for the ANN based location estimation unit which can be implemented on a low-cost hardware is also proposed in the chapter 4 . The chapter concludes with the performance analysis of ANN-LEU. Chapter-5 presents the work carried out to accomplish Objective 3. A two-dimensional, short- term self-localization scheme based on inertial measurement unit is proposed. For performing the crucial step in localization i.e. the activity detection, a Sugeno fuzzy inference system is proposed. The chapter concludes with the account of the performance analysis of the proposed self-localization scheme in localizing the robot for short distances.

Chapter-6 presents a detailed account of the work carried out to accomplish Objective 4. The desired characteristics of a task allocation scheme for multi-robot and swarm robotic system is discussed. A fully distributed task allocation scheme which can be utilized to solve the 8 different types of task allocation identified by the taxonomy of Gerkey and Matarić is proposed. The chapter also presents the simulation work carried out to evaluate the feasibility of the task allocation framework on Autonomous Robots Go Swarming (ARGoS) simulator.

Chapter-7 presents the summary of the major contributions of this work and presents the recommendations for further studies.