Abstract

Swarm robotics is a nascent branch of research which integrates the advantages offered by distributed computing, particularly fault tolerance and scalability into the field of robotics. Traditional Multi-Robotic Systems (MRS) utilized in vehicular assembly lines or warehouse transportation, utilize a limited number of complex robots which are mostly controlled by a central entity. Recently low-cost MRS systems are utilized in applications such as ambient assisted living systems in which robots serve as companions to human beings. However, robots in MRS are generally characterized by minimal cooperation among robots. Swarm Robotic Systems (SRS) on the other hand utilize decentralized, cooperative, self-organized, 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. Swarm robots also offer parallelism in their behaviour whereby multiple, cooperating, cost-effective robots can achieve a given task quicker than a single robot by dividing the task into sub-tasks and executing them simultaneously. Therefore, the interest in the development of swarm robotic systems is gaining momentum. Performance of low-cost MRS systems can be significantly increased if qualities of SRS are incorporated into them. Recently many applications have been proposed for utilizing swarm of robots in a wide spectrum of applications such as military operations, disaster management, search and rescue, precision agriculture, inventory management in a warehouse etc. Despite their potential benefits, swarm robotic systems are yet to be widely employed for real-world applications and are still confined to the world of academic research.

As the price of robots comes down with the advancements in related technologies there is growing interest in developing modular and flexible robots. There is an increasing need for developing appropriate protocols or algorithms which guarantee effective scalability, decentralized co-operative control and autonomous behaviour to the robots. For effective operations of SRS and MRS systems, individual robots are to be synchronized to a common notion of time. The synchronization enables effective real-time wireless control, cooperative data collection, navigation, task allocation and task migration in a distributed network of robots. Though 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, prior time synchronization is stated as one of the assumptions when time dependency is involved. Thus most of the research in SRS and MRS systems is still limited to simulation-based study.

Increased flexibility in movement, leading to performance improvement can be achieved if the robots can determine their position in the area of deployment. Moreover, data from a distributed network has significance only when the data is associated with a location stamp, in addition to the timestamp. Hence, another desired capability of SRS and MRS is the ability to determine their position in the area of deployment. The ability to determine the position is also referred to as localization. Robots in SRS or MRS should be able to localize themselves in the network to navigate and perform tasks in a coordinated manner.

Another important aspect in the design of SRS (also in MRS) is task allocation among the robots. Task allocation involves distributing and scheduling the set of tasks among a group of robots to achieve certain system goals taking into account the operational constraints. Task allocation is also commonly referred to as Multi-Robot Task Allocation (MRTA) problem. Most of the solutions suggested in MRTA is limited to allocating a single robot to a single task which is the simplest of the task allocation problems. However, with the increased cooperative behaviour offered by SRS, it is important that other types of task allocation including allocating multiple robots to multiple tasks are also taken into account.

This thesis work aims at developing solutions for three fundamental issues in swarm robot systems and low-cost multi-robot systems i.e. the time-synchronization, localization and task allocation. We address the problem of time synchronization for SRS and for scalable, low-cost MRS, which makes use of a wireless network for communication among the members of the swarm. Swarm-Sync, a novel, energy efficient, global time synchronization framework which utilizes WSN for communication among members of the swarm is designed and tested on robots in single hop and multi-hop scenarios. We demonstrate that the framework can provide a synchronization accuracy in the order of few hundreds of microseconds even in multi-hop scenarios, for resynchronization interval in order of several minutes (we have tested up to 10 minutes). Swarm-Sync is a scalable time synchronization framework and can provide a bounded synchronization error throughout the network, thus leading to the easier design of other layers of the protocol stack such as localization, task allocation and routing. The framework can be easily incorporated into any robotic protocol stack owing to its computational efficiency and flexibility to support on-demand or continuous synchronization. The framework can be utilized for indoor as well as outdoor applications.

Localization of SRS and MRS in indoor environments have been explored in detail in the thesis. Ultrasound beacon based localization hardware is designed and validated for accurate time of flight measurements. For location estimation, an artificial neural network based localization estimation unit (ANN-LEU) is designed. The performance of proposed location estimation unit is evaluated by simulation of various Line-of-Sight and Non-Line-of-Sight conditions generated in Locus simulator (Locusim) and suggestions for further performance improvement is presented. A self-localization scheme for localizing the robot for short distances is presented in the thesis. For performing activity detection, a crucial step in localization, a fuzzy inference system is proposed. The feasibility analysis of the proposed technique is validated for different test scenarios.

A Distributed, TDMA based Task Allocation (DTTA) framework for a swarm of robots which can be utilized to solve any of the 8 different types of MRTA problem identified by Gerkey and Mataric is proposed in the thesis. The proposed framework is reactive and can perform task migration via extended task assignments to complete the mission in case of failure of the assigned robot. DTTA framework isolates path planning and navigation from the task allocation problem and hence may be utilised for any kind of robot in land or for co-operative systems comprising of land robots and air-borne robots (drones). Dependencies with other layers of the protocol stack were identified and a quantitative analysis of communication and computational complexity is provided. Effectiveness and feasibility of deploying DTTA in real-world scenarios is demonstrated by simulation-based testing of the framework for two diverse application scenarios using Autonomous Robots Go Swarming (ARGoS) simulator.

The work presented in this thesis is expected to take the research in SRS and MRS, a few steps closer to utilizing swarm of robots or low-cost MRS in several human-friendly applications such as warehouse management, environmental monitoring, search and rescue, precision agriculture, etc.