Chapter 7

Conclusions and Future Scope

Presented in this thesis is a comprehensive summary of the study directed towards developing functional swarm and low cost mult-robot systems for real-world applications. The major factors which prevent the widespread use of swarm and low-cost multi-robot systems in practical applications were identified through detailed literature review. 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. The work presented in this thesis can be utilized for developing several practical systems such as robot-assisted living in indoor environments, search and rescue missions, green house monitoring in indoors or outdoors, etc.

7.1 Principal Contributions of the Thesis

- **Time Synchronization for Scalable and Dynamic Networks**
  This thesis identifies the desired characteristics of a time synchronization protocol for dynamic and scalable networks such as multi-robot, swarm robotic systems or mobile wireless sensor networks. A detailed empirical analysis on the source of error in techniques utilized for time synchronization in popular synchronization protocols which utilizes MAC level timestamping is presented. Experimental analysis of the two major class of protocols, i.e. the prediction based and consensus-based protocols have been presented in detail which highlights the necessity of developing a new time synchronization scheme.

Swarm-Sync, a novel, energy efficient, global time synchronization framework for a swarm of robots which utilize the wireless network for communication among members of the swarm is proposed in this thesis. The synchronization framework consists of two components- time offset compensation and frequency offset compensation. A unique characteristic of the proposed framework is that the framework utilizes only one-way messages for time and frequency offset compensation, as is desired for a scalable network. Popular synchronization protocols such as TPSN and RBS perform frequent time offset compensation and do not implement frequency offset compensation. The protocols which utilize LR, LP and KF techniques predict the reference node clock from timestamps obtained from reference and slave nodes without performing initial time offset compensation. Our experimental analysis on the existing time synchronization protocols indicates that the resynchronization interval can be significantly improved if the initial time offset compensation is performed on the nodes. However, the techniques for time offset compensation available in literature utilize two-way message exchanges resulting in "inter-sync" error leading to higher convergence time and are not suitable for dynamic networks due to the topological changes. We demonstrate that accurate time offset compensation can be performed using one-way offset messages.

A novel skew fingerprinting based frequency offset compensation scheme is presented. Most microcontrollers including STM32F407VGT6 used in our experiments are clocked using AT-quartz crystals which exhibit a cubic variation of skew with temperature. From the experimental analysis on the nodes which utilize AT-cut crystals, it can be concluded that the average relative skew fingerprints estimated at a given temperature can be used for frequency offset compensation, even in dynamic environmental conditions, if the poller node is stable for variations in temperature. To this effect, the poller node can be designed with a temperature controlled crystal oscillator (TCXO) or oven controlled crystal oscillator (OCXO) as the clock source. TCXO and OCXO incur higher cost when compared to the typical crystal oscillators used in microcontroller boards. However, their clock frequencies are stabilized for variation in temperature. TCXO or OCXO generated clocks exhibit unique relative skew which can be fingerprinted. However, the variation in frequency with temperature exhibited by them will be negligible. If the temperature profile of the deployment area is prone to wide variations or nodes in the system utilize crystals of different 'cuts', then utilization of TCXO or OCXO for all nodes is recommended.

The Swarm-Sync framework is decentralized and topology independent, hence the robots can navigate freely across clusters or hops without necessitating resynchronization of the network. The framework does not impose any restrictions on the movement of the robots. One of the unique and the important feature of the Swarm-Sync framework is that it can provide a synchronization accuracy in the order of few hundreds of microseconds, for resynchronization interval in the order of several minutes (average synchronization error of 110µs for resynchronization interval of 10 minutes) whereas the time synchronization protocols available in literature support a resynchronization interval in the order of few seconds only. The increase of resynchronization interval improves the energy efficiency of the system drastically and the communication bandwidth can be utilized for other robotic activities. Another significant feature of the synchronization framework is that it can provide a bounded synchronization error throughout the network, thus leading to the easier design of other layers of the protocol stack like medium access control, routing, localization and task allocation. The required hardware for the implementation of the Swarm-Sync framework was designed and the framework was implemented, tested and validated for single-hop and multi-hop networks. The suitability of the time synchronization protocol for dynamic environments is also presented. The work can be also be utilized for time synchronization of other dynamic distributed networks such as mobile wireless sensor network.

- **Development of Localization Scheme for Indoor Robotic Network**

  This thesis proposes, the a two-dimensional beacon based indoor localization scheme for robots in SRS and MRS. An ultrasonic, beacon based, two-dimensional localization system using Time of Arrival (ToA) technique, wireless network and an artificial neural network is presented. 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 or time of arrival measurements between of target and beacon node was developed. An Artifical Neural Network based Location Estimation Scheme (ANN-LEU) is proposed for localization under Line-of-Sight (LOS) and NLOS conditions. In the last few years several machine learning techniques are utilized by researchers to characterize the NLOS conditions using offline training process, followed by identification and removal of NLOS measurements during online measurements. However the available NLOS detection based localization systems are based on the offline learning of possible NLOS conditions and it is difficult to capture a comprehensive data set including the possible NLOS conditions in indoor environments. One of the unique features of the proposed location estimation scheme in this thesis is that the training of the system is needed to be performed only for the LOS conditions.

From the performance analysis of ANN-LEU following conclusions were derived. With three beacon nodes in LOS, out of the 70 target nodes randomly deployed in 4m x 4m, the Mean Average Error (MAE) in the position of 11.44 cm was obtained. For 92.64% of the nodes the error was restricted to 20cm and the RMSE error in position estimation was only 11.53cm.

The ANN-LEU can reliably identify the presence of NLOS if any, in the time of flight measurements. If the beacon nodes are placed in such a way that, the arc drawn from the two beacons do not intersect at two locations within the area of coverage, then even with two beacons, the location of target node can be estimated in a reliable manner using the proposed scheme.

The MAE in position estimated during the performance analysis was restricted to lesser than 20cm for LOS, and also for the scenarios in which one of the three beacon nodes are in NLOS (also when the arcs drawn by beacons do not intersect at two different points). This is a significant improvement in performance when compared to the performance of available indoor localization systems which provide an accuracy in the range of 1-2.5 meters under NLOS conditions utilizing 3-8 beacons as mentioned in Table 2.3.

The ANN-LEU could detect NLOS between more than 1 beacon node and target node with a precision of 91.9% (for 210 test inputs) and thus invalidating the incorrect position estimation if any. The performance analysis of the proposed localization scheme indicates that higher accuracy in positioning can be obtained with lesser number of beacons when compared to the other state-of-the-art ILS systems. The ANN-LEU based location estimation technique can be adapted for any ILS which is based on time of arrival (ToA) technique of beacon signal (e.g Ultrasound, Ultra Wide Band (UWB)).

Wireless beacon or infrastructure based localization as presented in Chapter 4 of the thesis can be employed for localization in indoor environments. However, In a large scale or medium scale multi-robot or swarm robotic system, if all robots rely only on beacons for localization, as the number of robots in the system increases the wireless channel bandwidth will be extensively utilized for the localization, rather than for other communications required for co-operative task completion. Hence to reduce the overall cost of implementation of the system and also for effective utilization of the wireless channel for other cooperative functionalities, it is essential that the robots can localize itself for at least smaller distances. Most of the work on indoor localization available in the literature is dependent on the type of the robotic vehicle. In this thesis work, a Fuzzy Inference System based self-localization scheme which makes use of only inertial measurement unit for localization is presented. The scheme together with the beacon based localization scheme can be utilized for developing the complete indoor localization system for SRS and MRS. The beacon based localization scheme can also be used for any other application which requires context aware servicing in indoor environments, such as in smart buildings, Ambient Assisted Living Systems etc.

- **Development of Fully Distributed Task Allocation Scheme for Swarm Robotic System**
  DTTA- a distributed, TDMA based task allocation framework for 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. DTTA replaces competitive bidding in traditional market based approaches with cooperative, self-task assignment in which individual members of swarm assign tasks to itself rather than the same being assigned by the auctioneer. DTTA 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 task allocation problem and hence can be utilized for any kind of robot in land or for co-operative systems comprising of land robots and air-borne robots/drones. The framework is suitable for clustered scalable networks. The major advantage of the protocol is that the computational complexity of the protocol is proportional to the number of robots required to service a given task rather than the total number of robots in the system. Similarly, the communication overhead is involved for a robot only if it will service a task/tasks. This framework can be utilized in any robotic network which maintains the notion of time and has the capability to determine its relative position in a given environment.

- **Soft Computing Paradigm for Solving Traditional Problems in a Mobile Network**
  This thesis explores the possibility of utilizing soft computing techniques for solving an

important problem in robotic network i.e localization. Artificial neural network and fuzzy inference logic are utilized to localize the robot in a given area. The soft computing techniques are capable of dealing with imprecision, uncertainty, and ambiguity which is usually present in real-world data. Moreover, an attempt has been made to utilize soft-computing techniques as much as possible instead of relying on mathematical models of the robotic structure or its kinematics, for localization, thus ensuring that the protocols can be used in any type of robotic structure.

7.2 Limitations and Future Scope

This study has few limitations which warrant further research.

- In this thesis, an effort has been made to develop the hardware as well as the software stack for development of techniques proposed in this thesis and validate the protocols in practical situations. However cost-effective, robotic platforms with the desired characteristics are not yet commercially available. Hence, 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 functioning 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 an existing autonomous robotic platform 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 huge development time. Hence there is a need for developing stable, cost-effective robotic platforms which facilitate research in this area.

- Research in distributed robotics often requires custom embedded hardware development in addition to software development. To test a novel technique or algorithm, it has to be simulated or modeled in simulation tools to evaluate its feasibility, independent of the limitations of the hardware platform. Simulations are essential in situations where performing tests with actual hardware is prohibitively time-consuming, expensive or laborious. However, often separate coding techniques are required for the simulation and for the implementation of the same on hardware. Efficient tools which port the simulation code to hardware specific code will facilitate shorter development cycle.

- In this thesis, Inertial measurement units were explored for assisting the navigation of robots for shorter distances for cooperative formation control or for short distance "go-to-goal" missions. Although the results achieved through the study indicate that localization using IMU is feasible, the same has to be explored further for localization in 2D or 3D environments. There is a scope for developing programmable application specific integrated circuits (ASICs) which provide accurate on-demand localization, so that the computational unit of the robot is offloaded from the task of positioning of robots. Also, the Sugeno Fuzzy Inference System (FIS) utilized for activity detection in this thesis, lends itself to the use of adaptive techniques such as Adaptive Neuro Fuzzy Inference Systems (ANFIS) which can be used to customize the membership functions of FIS so that the fuzzy system best models the input. With the programmable ASICs, the membership functions of a Sugeno FIS may be fine-tuned or trained for the specific application, after which the same can be utilized as a stand-alone localization engine. Also, a Neural network based robust Location estimation unit is presented in this thesis. The hardware implemetation of the same can be explored further. Also, further studies are required in developing ultrasonic transducers which provide improved transmission beamwidth.

- The feasibility of task allocation scheme presented in the thesis was evaluated using ARGoS simulator which supports ideal wireless communication model. In networked multi-robot and swarm robotic systems, inter-robot communication is a deciding factor which influences the dynamics and performance of the system. The control policies for the robots have to be evaluated under the inherent unreliability, uncertainty and limitations in the medium access and routing of messages to ensure that the systems are robust against communication errors. To reduce the efforts and costs involved in setting up real robots, appropriate simulation tools which integrate the available multi-robot simulators with network simulators are essential for rapid prototyping and deployment of multi-robot systems. Unfortunately, existing multi-robot simulators do not provide advanced communication models. ARGoS support interface for network simulators like Network Simulator 2 (NS-2) and Network Simulator 3 (NS-3).

However, the interface is not yet fully functional. Integration of network and robot simulators will facilitate quick and efficient testing of new concepts, strategies, and algorithms.