SELF-CONFIGURABLE COMMUNICATION NETWORK FOR WIRELESS MULTI-ROBOT TESTBED

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
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This document is dedicated to my loving family.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Abstract of Thesis Presented to the Graduate School
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The Multi-Agent Systems (MAS) have been studied over decades. Various issues were well discussed conceptually. The implementation of MAS on the physical hardware is an important phase for the research development. Hardware validation process promotes the theoretical concepts to realistic problems. Nevertheless, the hardware implementation is somewhat costly and sophisticated. A multi-robot testbed is a cost effective solution to implement different concepts for MAS.

This research proposes an architecture for the hardware implementation of a MAS. A description about the design of a wireless multi-robot testbed for further MAS research is provided. Relevant research topics including path planning and cooperative control are also briefly introduced in the thesis.

Meanwhile, the communication is a prerequisite before the validation of MAS. The work in this thesis will mainly focus on the network architecture for the communication between robots. The objectives for the network communications are to simplify the

existing framework and maintain the flexibility for any further revision. Also, in order to enable the inter-cooperation between robots, the agent communication language is used to provide a standard for the conversation.

Moreover, the MAS provide a decentralized control scheme for the system. It is more robust for any exceptional incidents and failures. In order to enable a more robust communication environment, the self-configuration of the network topology is proposed in this thesis as well. For such a self-configurable network, the failure of the robot for the communication can be accommodated. Dynamic adjustment to an optimal topology could therefore be made.

The work presented in this thesis provides a hardware solution for MAS research. The self-configurable topology offers a flexible network scheme for wireless communication and decentralized control scenario.

CHAPTER 1
INTRODUCTION

Multi-Robot Systems (MRS) have brought the robotic researches into a new paradigm. Not only the functionalities but also the cooperative operations between robots have excited the interests and attentions of the robot communities. The widely applicable MRS research could be mainly divided into three categories: space-based, military and civilian uses. Moreover, for some of the issues, for example, cooperative control, path planning, and communications have become more and more important to the development of MRS. However, the physical implementations of such systems may be restricted by the limitations of hardware. The dimension of the robot body, extra payload, the performance of the sensors and actuators, or the controller's information process capability could all substantially affect the overall performance. In addition, the communication capability is one of the restrictions for some implementations like spacecraft communications or smaller size robots. In this chapter, the applications for MRS and the corresponding issues will be mentioned. This effort will facilitate a further integration of the hardware implementations provided in the thesis as well as the network communication design into a larger framework of the MRS research.

1.1 Applications of MRS

Traditionally the robot communities focused their research interests in the domain of the single robot applications. However, with the growth of the semiconductor and communication technologies, for example, MEMS, wireless network and Global Positioning Systems (GPS), the development of mobile robot technology has been transferred to the multi-agent level. The studies of the cooperative and collaborated control for MRS has been extensively discussed and implemented since last decade (see JRP [2]). The applications for MRS are fairly diverse from military unmanned espionage, mine sweeper to rescue or space exploration mission. The following section summaries all the applications into three major application categories – military, civilian, and space-based. Some relevant developments will be mentioned as an example..

1.1.1 Military Applications

The effort to apply the MRS research for military uses has been initiated and performed by several agencies and programs, for example, Defense Advanced Research Project Agency (DARPA) [1] and Joint Robotics Program (JRP) [2]. The objectives for the robot researches within these programs include:

- Increase the autonomous mobility
- Refine the tactical behavior
- Design the innovative platform
- Minimize the robot dimension

DARPA has been successfully been merged the cutting edge technologies into the robot researches in the past couple of decades, for example, the communications and artificial intelligence enhance the controllability and autonomy on the robot. Figure 1.1 shows the major accomplishments by DARPA since 1960s. With the current achievements on the communication systems, for example, GPS technology, the mature of the network development and the various artificial intelligent algorithms for the autonomous behavior, the Multi-Agent Systems (MAS) could have been able to promote the status from software agents to physical agents. Therefore, as for the military applications, the MRS including various unmanned vehicles would become new thrusts for the warfare development.

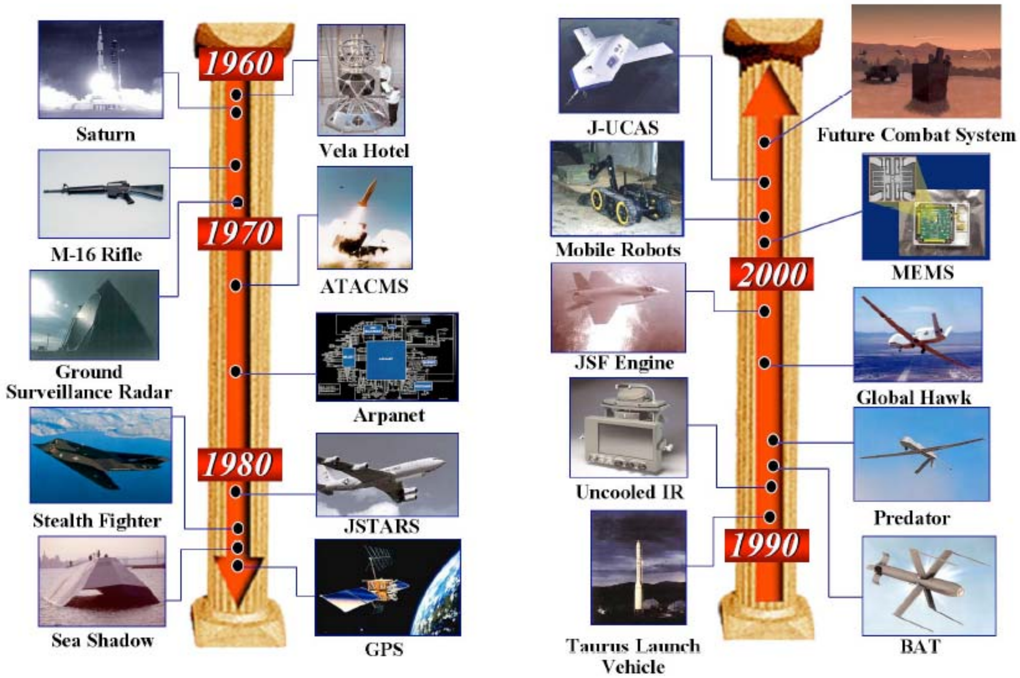


Figure 1.1 Key DARPA accomplishments since 1960s. [1]

Moreover, the integration of separate Unmanned Ground Vehicle (UGV) robotics developments and projects had also been made into the Joint Robotics Program [2] by the Office of the Secretary of Defense (OSD) in 1990 at the recommendation of the Senate Appropriations Committee. This effort also advances the successfully global deployments of UGV in some of the military operations including Bosnia, Afghanistan, and Iraq in the past decade.

UnManned Systems (UMS) have been validated widely during the mentioned ongoing services. UMS as described in the concepts below are envisioned to contribute the increase of mission effectiveness and are planned for integration into service force structures [2]:

- Army – Future Force: Future Combat Systems (FCS)
- Marines/Navy – Gladiator Tactical Unmanned Ground Vehicle: Autonomous Operations
- Air Force – Air Expeditionary Warfare: Robotics for Agile Combat Support and the Airborne Explosive Ordnance Disposal Concepts

However, the goal of JRP has been to develop a diverse family of UGVs and to foster service initiatives in ground vehicle robotics to meet requirements for greater mission diversity and increasingly more autonomous control architectures [2]. As in Figure 1.2, the maturation and transition of the technology to the robotic systems will feature the robotic services with more autonomous capabilities. Therefore, the enhanced object recognition and tactical behavior could enable the use of robotics to a fairly extensive and effective manner. As it is shown in Figure 1.2, the advanced technologies such as route planning, mission planning and target recognition will lead the MRS from a teleoperational service to a more and more autonomous service. As in the current progress of MRS, the system is undergoing the development of route planning and heading to a mission planning level, where the robot autonomy will exceed the level of human intervention. Both the route planning and mission planning have the critical need to perform the dispatched tasks cooperatively. Such a cooperation behavior requires a reliable and robust communication system. Moreover, a further advance phase in Figure 1.2 requires higher and higher communication data rate. Therefore, the importance of the communication system in a MRS will be higher and higher.

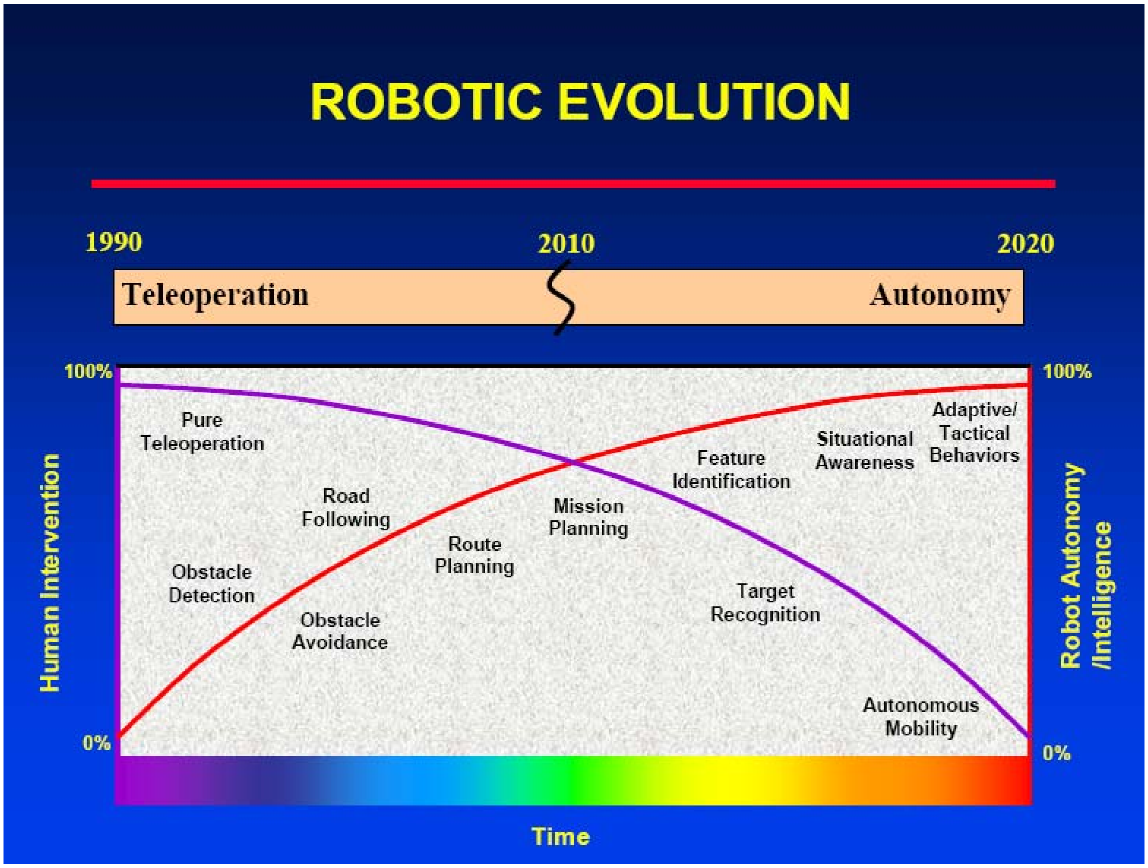


Figure 1.2 Robotic evolution. [2]

1.1.2 Civilian Applications

The efficiency and effectiveness of the MRS can not only facilitate for military purposes but also benefit civilian uses. Sometimes the tasks are too complicated for a single robot and we need multi robots to work cooperatively. For example, the search and rescue mission using multiple vehicles will influentially decrease the time required to complete the mission. Multiple robots can also be used for moving a larger object. Brief descriptions on some of the general applications will be discussed in this thesis.

1.1.2.1 MRS for jet engine inspection

The maintenance of the aircraft is critical to the aviation safety. Jet engines undergo examinations for detecting potential flaws on the surface of their components, such as cracking and erosion. Usually inspection methods are usually either the invasive borescopic or a full teardown, both of these methods are time-consuming. Full teardown, however, is even more time consuming and costly, and is often applied for only the situations when damage is detected and the replacement of parts is necessary.

NASA Glenn Research Center [3] proposed another approach for the inspection of the jet engine health. Instead of manual inspection procedures, miniature mobile sensor platforms could provide another option. The mobile robots equipped with the vision and communication systems can roam arbitrarily on the surfaces inside the engine. The robots could hence send the internal image of the jet engine back to the station. Therefore we can go through the engine inspection process with less human power and time. Figure 1.3 and Figure 1.4 show the miniature mobile robots in the inspection concept.

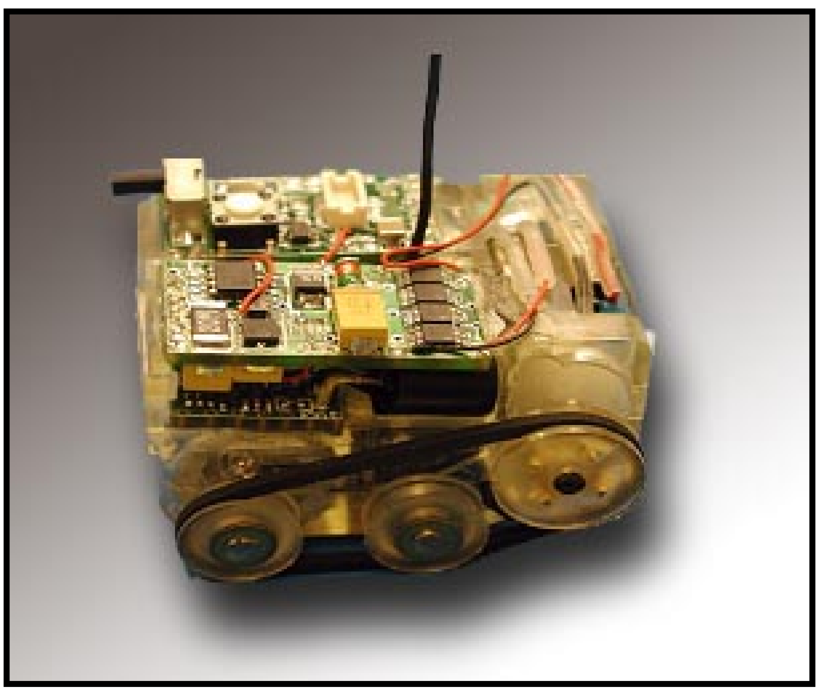


Figure 1.3 NASA Glenn miniature mobile sensor platform. [3]

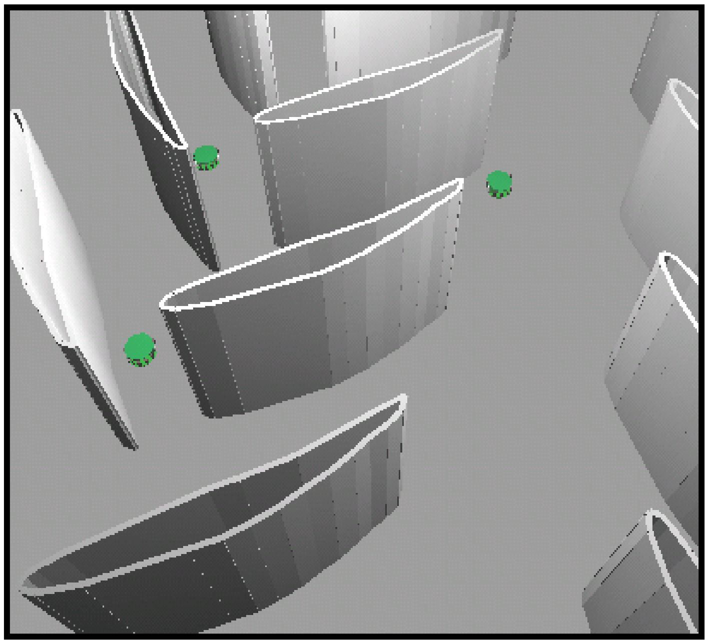


Figure 1.4 The concept of jet engine inspection. [3]

1.1.2.2 Robot soccer competition

The concept of robots playing soccer was first introduced by Alan K. Mackworth [4] in 1993. By using the global vision system, the main station could acquire the orientation and position of each different robot. A wireless communication is also required to transmit the commands to the robots. An artificial intelligence is involved to determine the strategy to compete against the other team. In July 1997, the first official conference and games were held in Nagoya, Japan. Followed by Paris, Stockholm, Melbourne and Seattle where the annual events attracted many participants and spectators [5]. There are five different leagues in the RoboCupSoccer: simulation league, small size league, middle size league, four legged robot league, and humanoid league. Comparing to the other MRS applications, robot soccer is highly dynamic and the state change is in real-time. No human intervention is allowed during the period of the game. Its situation in a MRS development phase contrast to Figure 1.2 is a more advanced phase including the object recognition and situational awareness. The research fields cover various areas from artificial intelligence to robotics. Such areas include real-time sensor fusion, reactive behavior, strategy acquisition, learning, real-time planning, multi-agent systems, context recognition, vision, strategic decision-making, motor control, autonomous robot control and more. Figure 1.5 is the picture of a competition in the small size league in RoboCup 2004 at Lisbon, the regulation restricts each robot must be able to fit inside a 180mm diameter cylinder. In Figure 1.5, different colors and marks at the top of each robot is used to identify the position and orientations of different robots from cameras.

Figure 1.5 Small size league in RoboCup 2004. [5]

Due to the dimension restriction, the control of the whole team is usually somewhat centralized in order to reduce the onboard processing need. A global vision system is then used to trace the robots and ball. The control diagram is in Figure 1.6. The hardware architecture adopted in Figure 1.6 is, however, fairly similar to the wireless multi-robot testbed we will discussed later in the thesis. An overhead camera system is used as the object positioning system for the robot localization. The image processing is dealt by a base station, and proper control commands for the robots are transmitted by a wireless transceiver. Therefore, the robot soccer can also be taken as a platform for the evaluations of various MAS concepts, as the same purposes for the wireless multi-robot testbed.

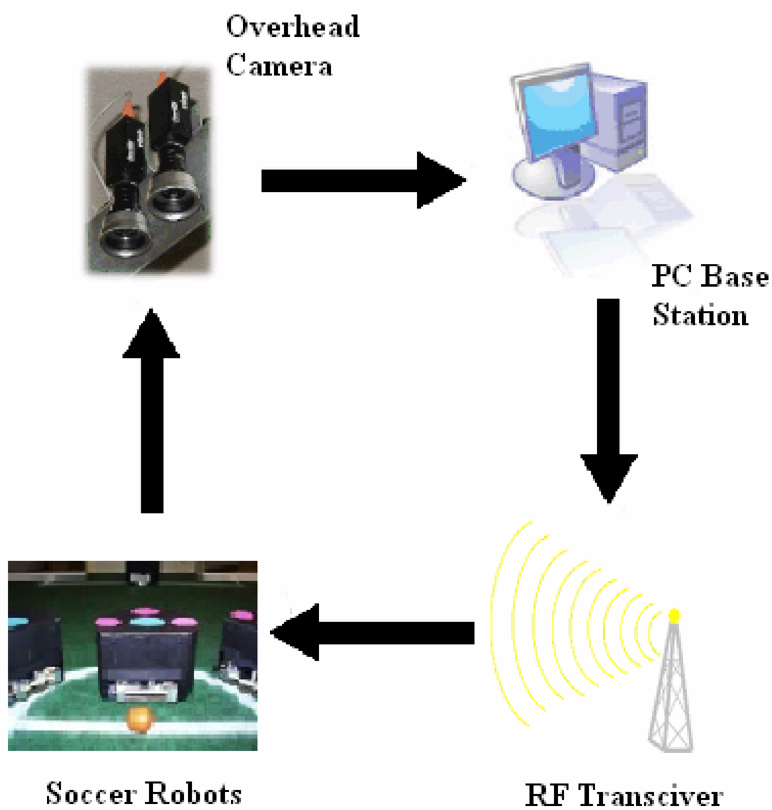


Figure 1.6 Control diagram of robot soccer.

1.1.2.3 Multi robot search and rescue

The task of search and rescue can be performed by a single robot. RobotCup [5] also has a separated domain called RoboCupRescue. The robot is required to be operated in a dedicated scenario autonomously. However, the cooperative multi-robot search and rescue operation could greatly increase the efficiency or enable some capabilities which couldn’t be performed by a single robot. James S. Jennings et al. [6] discussed the cooperation of robots for a search and rescue mission. The following capabilities are required to perform such tasks.

- Navigation and localization
- Search
- Object recognition
- Communication with other members in the team
- Cooperative manipulation of large objects

The MRS demonstrated in Figure 1.7 is named as “MOVER”. The algorithm of the proposed MOVER system [6] performs the task in Figure 1.7 by the following steps:

Step 1: A workstation and 5 robots idle for the initial status.

Step 2: The workstation initiates the program to perform the search and rescue.

Step 3: All robots start to search the house shape object.

Step 4: One robot finds the target while all the other robots still searching.

Step 5: The robot that found the target notifies all the other robots that target has been found.

Step 6: The other robots are heading toward to the target.

Step 7: Another robot arrives the target and notifies other robots.

Step 8: The last robot arrives the target and notifies other robots.

Step 9: All the robots manipulate the target toward the intended location collaboratively.

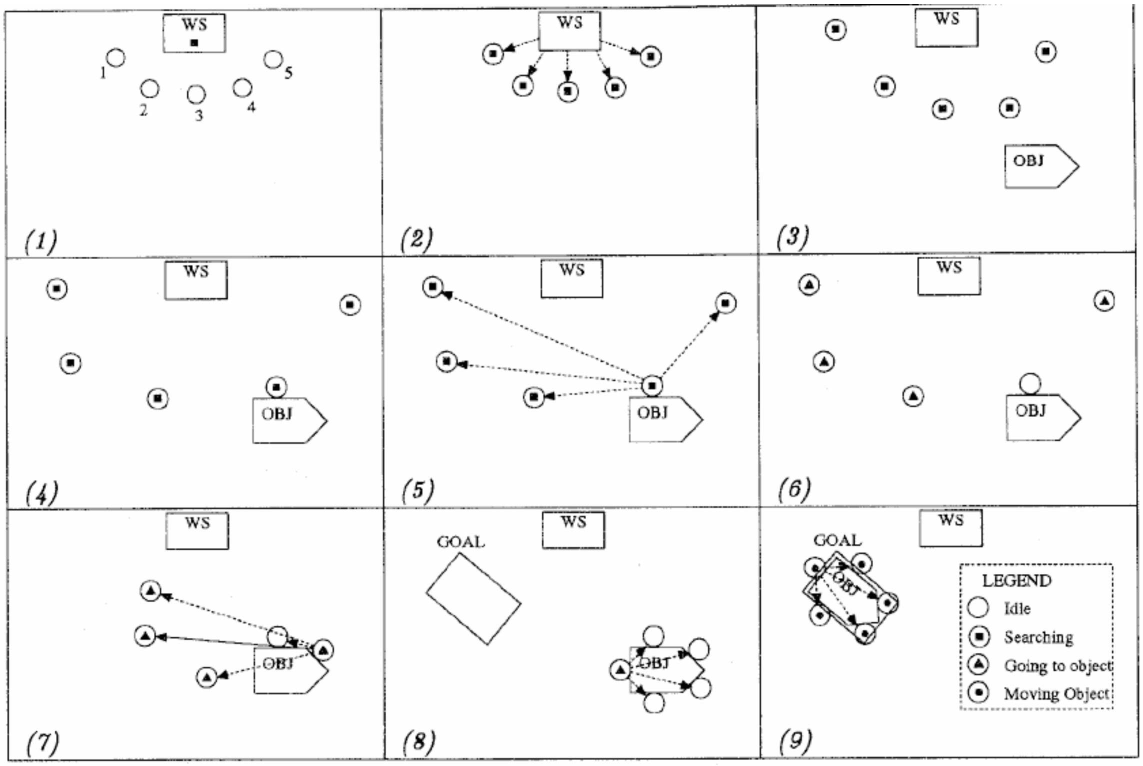


Figure 1.7 Search and rescue operation by MOVER system. [6]

1.1.3 Space-Based Applications

The MRS researches have also been studied in many of the space mission projects, for example, NASA's Mars exploration project (See NASA [7]) and the Demonstration of Autonomous Rendezvous Technology (DART) mission (See NASA [8]). The space-based applications varied from formation flying, cooperative control for multi-arms, to autonomous mobile robots for space exploration. Comparing to the terrestrial-based applications, the space-based applications usually have more serious technical concerns in the following characteristics:

- Uncertain environments
- Communication delays
- Limited sensing and actuation
- Scalability

Dani Goldberg et al. from Carnegie Mellon University [9] discussed the synchronization and coordination for mobile robots for the application to space exploration. The Mars exploration scenario has been set in the discussion. The distributed layered architecture is proposed for the highest possible scientific return on the given tasks. Due to the limitations on the communications (bandwidth and latency), the centralized control is not reliable. So the robots are responsible for making the decisions based on the priority of the tasks and how the tasks are to be accomplished. The architecture is shown in Figure 1.8. The planning layer sends the plans to the executive layer, which could further decompose tasks into subtasks and dispatch them based on the temporal constraints imposed by the plan. The behavior layer is responsible for the control of the robot or updates the information from the sensors or the status. Also, the executive layer is responsible for monitoring the tasks status and returning them to the planning layer. This layered architecture can be also used on a single autonomous robot. It is shown in Figure 1.8.

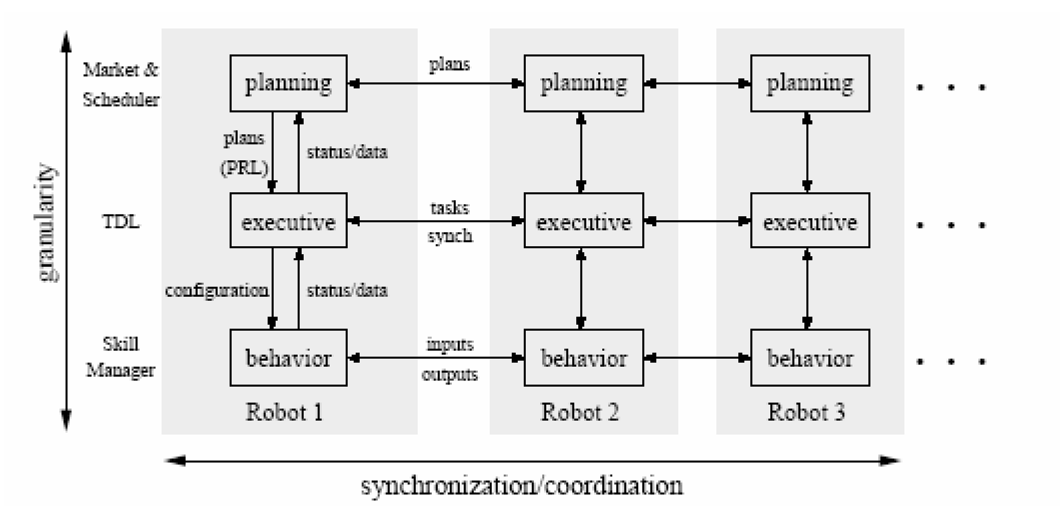


Figure 1.8 Layered multi-robot architecture. [9]

In Figure 1.8, each robot has the mentioned three layered architecture. The communication can occur either vertically between either different layers on the same robot or horizontally the same layers on different robots. The information of sensor data, plans, or tasks in this architecture could hence be exchanged and coordinated. However, the communication performance in this architecture dominated the system performance. Requirements for a higher bandwidth and lower latency communication in order to coordinate the action are needed, which might not be always allowed.

1.2 Fundamental Issues

The various applications presented above show different requirements and restrictions. A good understanding on the potential factors that might affect the performance or feasibility of a MRS application is critical. A system design or evaluation must be provided under these considerations. Therefore, the following key factors to the MRS application would be addressed in the section:

- Autonomous behavior
- Cooperative operation and communications
- Hardware restriction

1.2.1 Autonomous Behavior

Some applications only require the base station to centrally control different robots. However, since the robots don't take charge of the data analysis, the information gathered by various sensors on different robots need to be transmitted to the base station. Also, for the simplicity of the communication, the information will mostly be shared on only the base station. The drawback of the non-autonomous robot is it can't be operated unless the control command is given from the base station. Therefore, the non-autonomous robot itself can be taken as no more than a set of sensor/actuator instead of an intelligent "agent". Nevertheless, the obvious advantage is the design of such a MRS system can hence be greatly simplified and much easier to be implemented. An example of non-autonomous MRS is the small size robot soccer mentioned earlier. The hardware requirement for an autonomous system is usually depending on the computational and environment sensing needs. From IR sensor, voice detection, thermometer, to relatively complicate systems as well as the vision system or laser range detector could all be possible options for an autonomous system.

As the earlier discussion, the developments for a MRS toward system autonomy have several different phases from pure tele-operation to full autonomy (See Figure 1.2) during its evolution. Many of the centralized controlled systems are still capable for low level maintenances and fault detections. However, the high level task schedules or tactical behaviors still need to be assigned by the central station. Multi-robot search and rescue is usually operated under this mode. Each robot in the system can perform its task to search the possible target autonomously. The decision making is determined by the base station. Another example is the satellite system. Navigation, attitude control, or health monitoring modules provided onboard can have the satellite to survive without base station under its autonomous behaviors on the orbit. However, the determination of the flying orbit or docking with other spacecraft is still currently controlled by the commands transmitted from the ground station.

The design of the necessary autonomy level for a system is mission dependent. Cost effectiveness could vary case of case. For example, the cost of the implementation for the vision on a small size robot (< 180mm) is usually expensive. Not only the consumption for the vision module but also the improved capabilities to process the image data. Communication or power system may also need to be enhanced in order to meet the operation requirement. This may be a big challenge to be implemented on an embedded system and significantly increases the cost of a system.

1.2.2 Cooperative Operation and Communications

Another critical issue for MRS is the cooperation of the robot operation. Cooperative operation can be used on a MRS to improve the task performance or enable additional features. The time interval spent to search over a terrain will be significantly reduced by using multiple robots. Also, the cooperative localization can help each robot locate itself and understand the scene better. Sometimes the assigned task is too complicate for a single robot to accomplish and needs to be executed by multiple robots. For example, NASA's Planetary Surface Robot Work Crew [10] coordinates the grasp, transport and placement of extended structure using multiple robots, as in Figure 1.9. The formation and cooperative control must occur in such a scheme.

A cooperative operation includes many different level problems from task assignment and schedule to the cooperative control and localization. One of the most essential components for cooperative control on MRS is communication. An autonomous robot can have the interactions via environment or sensing without any communication [11]. However, in most situations, the most effective method to share and update required information with each other is a data network. Multi robot search and rescue requires the sharing of information gathered from different sensors. As the operation procedures mentioned in Figure 1.7, the collaboration requires robots communicate with each other as a network. G. Kantor et al. [12] discussed the using a network of distributed mobile sensor systems for an emergency response problem. Multiple radio beacons have been deployed in the target building in order to estimate the gradients of temperature in the building in the discussion. The communication network is a prerequisite for many cooperative operations.

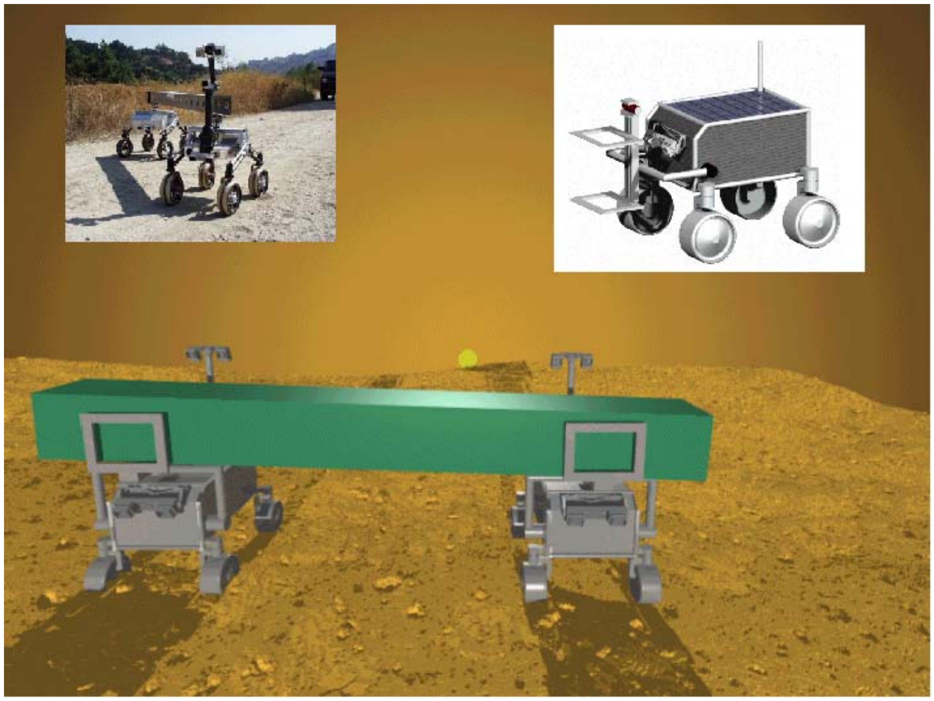


Figure 1.9 Planetary Surface Robot Work Crew (RWC). [10]

1.2.3 Hardware Restriction

The hardware restriction dominates the capability of the MRS. For the mobile robot, the resources are sometimes fairly limited in the system. The power supplied on the robot determines the capabilities of the embedded modules: the controller, all the working sensor and actuator subsystems. Unfortunately, the battery is sometimes relatively large, heavy and a considerable part of the total weight, which might deteriorate the overall performance or disqualify the system requirements. However, the autonomous system or decentralized control often requires better processing capabilities, which results in higher power consumption. For the physical restrictions on the mobile robots, there are some important considerations for a hardware design [11]:

- Centralization/decentralization

- Differentiation
- Communication structure
- Modeling of other agents

A careful review on all of these factors must be made and taken into consideration while dealing with the design problem for the MRS. An example design for small satellite for multi-spacecraft mission can be found in [13].

1.3 Methodology

In the previous section several issues for the MRS have been addressed. They are critical factors to the MRS. The existing solutions for these issues will be discussed in this section now.

1.3.1 Autonomous Behavior

The autonomy for the robot system involves many different disciplines. Image process, control algorithm, artificial intelligence, and motion planning may sometimes be needed for an autonomous system. An important aspect of the autonomous behaviors for a mobile robot is Motion Planning (MP). Moreover, a mobile robot is often required to be able to explore in an uncertain terrain. Hence, sensing, obstacle avoiding and planning for the optimal path would be the most critical problems for the mobile robot.

Y. K. Hwang and N. Ahuja [14] summarize the recent developments for motion planning problems. Before the discussion of motion planning, we need to classify the type of the problems and problem solving algorithms so appropriate algorithms could be highlighted regarding to specific problems. Table 1.1 and 1.2 list the classifications of different problem types and approaches. Also, a proper method to describe the environment, including the robots and obstacles, is essential to MP problems. Instead of using the classical world space representation, which the physical space robots and obstacles exist in, configuration space is more frequently mentioned in MP study. Configuration space is a set of parameters that completely specify the positions of every point of the robot or obstacle.

Table 1.1 Classifications of motion planning.

	Yes	No
Can objects change shape?	Conformable	Non-conformable
Time varying?	Time Varying	Time invariant
Restriction on the motion of robots?	Constrained	Unconstrained
Availability of the obstacle information	Dynamic	Static

Table 1.2 Classifications of MP algorithm.

	Limited	Unlimited
Completeness	Heuristic	Exact
Scope	Local	Global

Various approaches have been developed for MP problems. The applicability of each algorithm may be wide or restricted. Nevertheless, most of the algorithms could be separated into the following approaches [14]: skeleton, cell decomposition, potential field. Different approaches are not necessarily exclusive. Between these algorithms, the technique used to solve the MP problem is sometimes a hybrid method. A better performance could sometimes be obtained via the hybrid algorithms.

- Skeleton

The major advantage of skeleton approach is the simplicity of calculation. It simplifies the MP problem into a network of one-dimensional lines so the search can be restricted in the connections between nodes. This algorithm includes three phases. In the first phase, the robot moves from its initial configuration to a node in the skeleton. In the second phase the robot moves from a goal configuration to a node in the skeleton. The third phase connects two points by using the lines in the skeleton. Figure 1.10 shows the visibility graph of polygon in the plane. S and G in the figure represent the starting position and goal position respectively. The visibility graph is the collection of lines in the free space that connects different features. There are $O(n^2)$ edges in the visibility graph. n is the number of features.

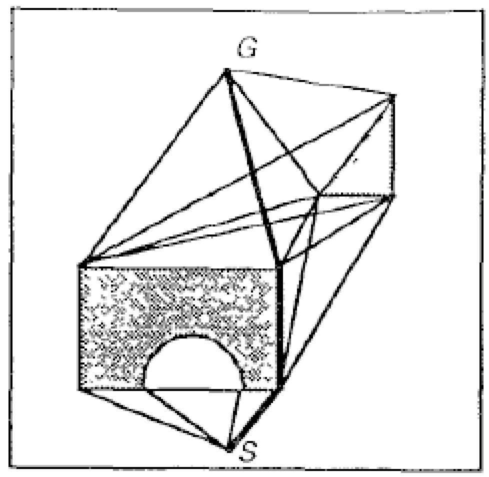


Figure 1.10 The solution path is shown in the bold lines in the visibility graph. [14]

- Cell Decomposition

The cell decomposition, as the name suggested, decomposes the free space into a set of simple cells. For the motion planning, we also need to compute the adjacency of the cells. The decomposition approach can either be object-dependent or object independent. The object-dependent method requires less cells. However, the computation complexity for the boundaries and adjacencies is high. It is shown in the Figure 1.11. First we decide the boundaries and adjacencies of cells by all the sidelines of the obstacles. Then we could determine the cells including the path from S to G.

The object-independent decomposition generally uses more cells. However, the calculation is less specifically for nontrivial objects. Quadtree [15] is used for a 2-D motion planning problem, or octree for a 3-D motion planning problem. The motion planning by quadtree is shown in Figure 1.12.

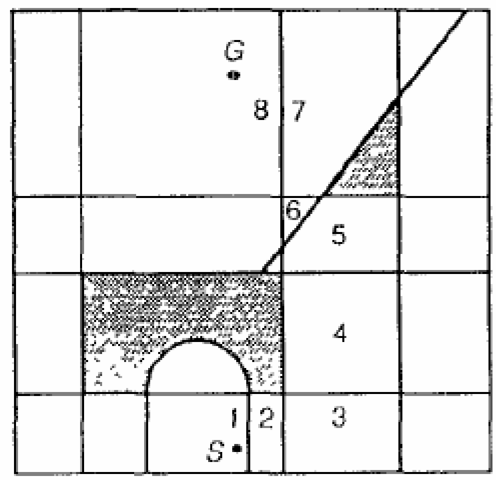


Figure 1.11 Object-dependent cell decomposition. [14]

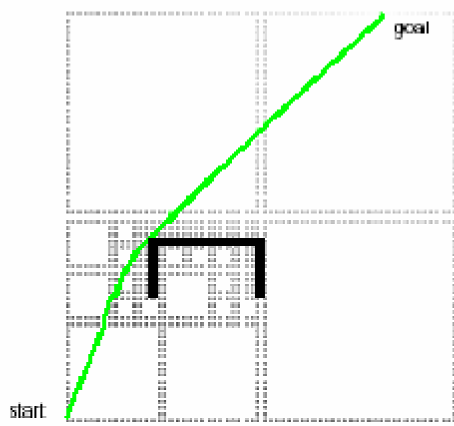


Figure 1.12 Quadtree motion planning. [15]

- Potential Field

The potential field constructs the environment by using the scalar function called potential. The goal configuration is set to be minimum, and a high value at the occupied space. The function is sloping down anywhere else toward the goal configuration. By this potential setting, the robot could therefore reach the goal configuration by following the negative gradient. The example of the potential field is in Figure 1.13.

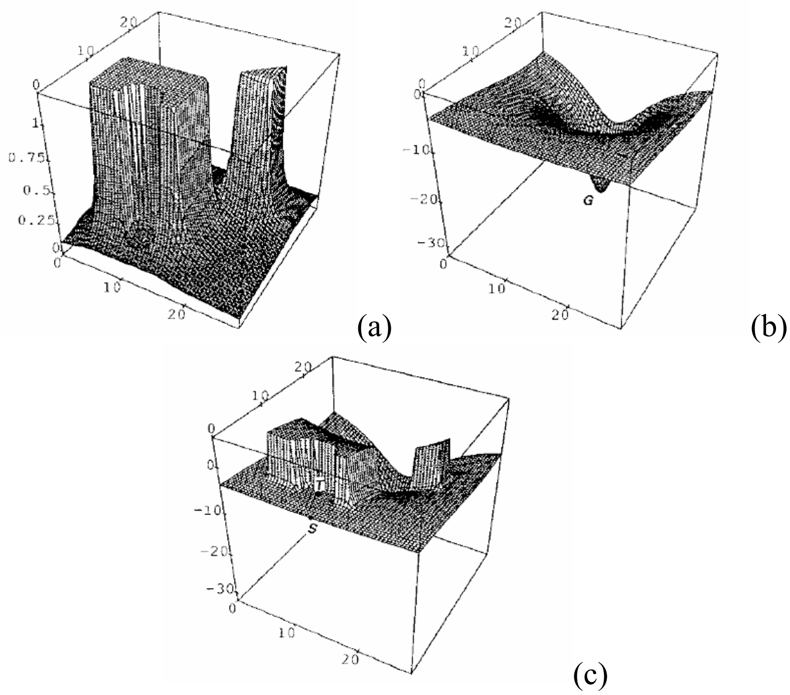


Figure 1.13 Function of the potential field. [14] (a) Obstacles has high potentials, (b) The minimal potential locates at goal, and (c) The path to the goal from start could be found along the negative gradient.

It could be observed from above discussions of various MP methods that a global understanding to the environment is a requisite. This can be solved by either using a global positioning system or a cooperative data sensing network, which will be mentioned in the next section.

1.3.2 Cooperative Operation and Communication

The cooperative operations for the MRS system are diverse. Different cooperative behaviors are developed, for example, formation, sensor fusion, cooperative localization and control. The disciplines involved to solve these problems are also very different. Three most common issues are mentioned here.

- Formation control

The formation problem is the most frequently discussed problem in the mobile MRS. It is the fundamental problem to control mobile vehicles. Many applications like search and rescue operations, robot soccer, formation flying of Unmanned Air Vehicles (UAV) required the cooperation between vehicles. Reza OlfatiSaber and Richard Murray [16] uses a set of parameters to present the formation graph. Then by using a structural potential function, the local collision free stabilization of formation of multiple vehicles can be obtained. Figure 1.14 (a) and (b) shows the formation for 3 and 6 vehicles respectively.

- Data fusion

The MRS application usually requires the system to be operated in an uncertain environment. Therefore, the capability to sense the environment becomes an important function. Sensing can include simple measurements from temperature and range to obstacles, to sophisticated multimedia data. However, the sensing information from different robots needs to be further fused in order to gain a better understanding of the environment. The methodology to exchange, process, or integrate the information becomes another issue. A distributed mobile sensor system is mentioned in [12]. The dynamic localization of all devices is estimated by Kalman filter, Markov method, and Monte Carlo. The location estimation of unknown tags by Kalman filter is shown in Figure1.15.

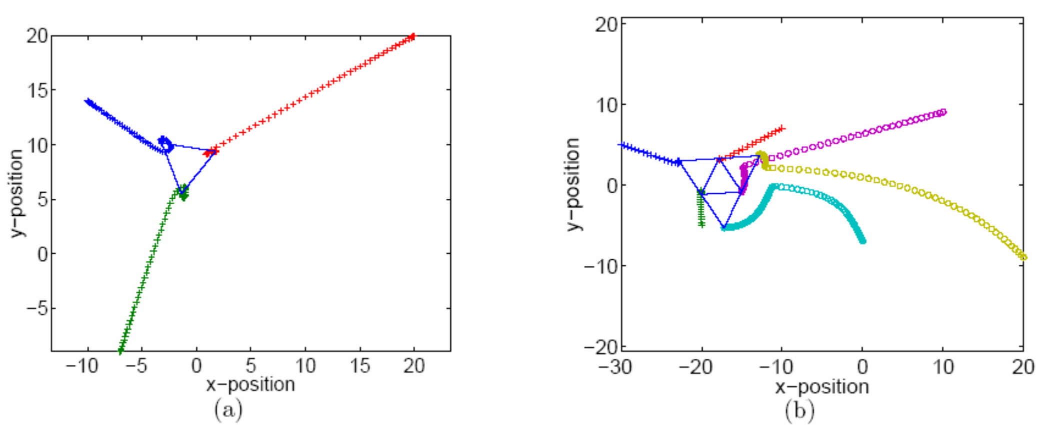


Figure 1.14 The stabilization of formation control. [16] (a) formation for 3 vehicles and (b) formation for 6 vehicles

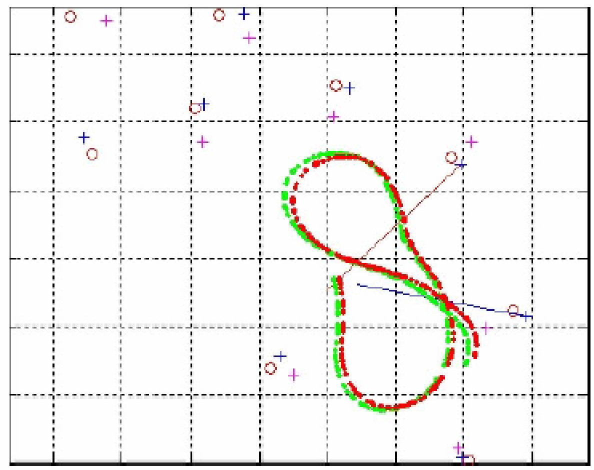


Figure 1.15 Estimation of sensor positions using Kalman filter. (“o” is the true location, “+” is the estimation)

The temperature gradient map is generated then by the ad-hoc network of the Mote sensors, as in Figure 1.16. Therefore, the temperature inside a scene can be dynamically monitored and the better decision to rescue lifes can be made.

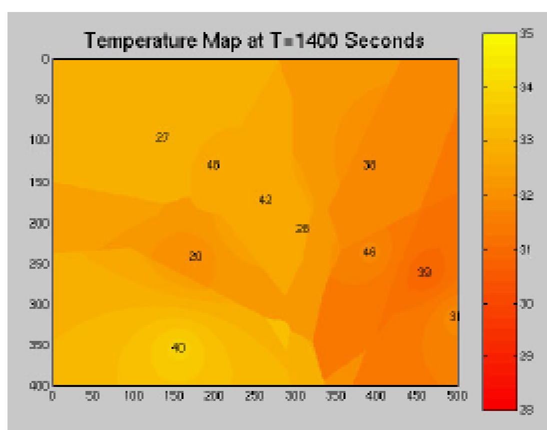


Figure 1.16 Temperature gradients inside the target building.

- Task schedule

A distributed layered architecture for mobile robot coordination is proposed in [9]. The autonomous high level task decomposition and subtask dispatch service, especially for time stringent cases and cooperative behavior, are mentioned. However, for non-time stringent mission, that the delay of operation will not cause catastrophic effects, a market based auction mechanism is proposed by Brian P. Gerkey and Maja J. Matarić[17]. The mission is constructed into a hierarchical structure first. The child task must be performed before the parent task is performed. The parent task is responsible for assigning child task to the robots and monitoring the status of the tasks. The auction is processed in the following steps:

1. Task announcement
2. Metric evaluation
3. Bid submission
4. Close of auction
5. Progress monitoring/contract renewal

The purpose of the auction mechanism is choosing the most appropriate agent to execute the task. The assumption here is the auction is always won by the most appropriate agent. This concept will later be used for a network self-configuration procedure.

1.4 Motivation and Scope of the Research

A common component for all level problems for cooperative behavior mentioned above is the communication. Just as with human beings, communication is a requirement for a successful cooperation. Also, for the mobile robot, wireless communication is needed instead of the communication through wires. The wireless Ethernet protocol IEEE 802.11 provides a well developed solution for wireless communication network. However, for some physical restrictions, like signal coverage, reliability and hardware complexity, IEEE802.11 could not always occur in all of the MRS, especially for deep space applications. The cooperative control scheme for the MRS could be mainly divided into two types: decentralized and centralized. It also relates to the communication architecture and many other factors. Table 1.3 compares the differences of the centralized and decentralized control. More details about the differences for communication will be discussed in the next chapter.

Table 1.3 Comparison of centralized control and decentralized

	Centralized	Decentralized
Hardware requirement	Low	High
Autonomy	Low	High
Communication architecture type	Infrastructure	Ad hoc
Communication complexity	Simple	Complicate
Communication direction	Unidirectional/Bidirectional	Bidirectional

The research interest in this thesis is mainly focused on the hardware implementation and the communication network solution. For centralized control, some simple architecture, for example, channelization is often used for communication network to share the medium. However, a central station must be used and constantly update the status in order to keep all the devices functioning. A service like packet switching or virtual circuit switching is often required to be provided for a decentralized control scheme. As the potential issues discussed above, a generic wireless Ethernet solution can not be adapted by all the MRS design. Proper modification must be made in order to customize the communication system to fit the specific scenario and other hardware designs. Chapter 2 will offer a technical review on the network developments before the presentation of the wireless network design. Several network considerations like hidden terminal problem and ARQ will be implemented on this network. The effort provided in the thesis is a minimal wireless network infrastructure for a wireless MRS testbed. It offers a wireless networking solution for a small size MRS for the distributed control purposes.

CHAPTER 2
NETWORK COMMUNICATIONS

The importance of communications has been laid out with the discussion of chapter 1. Network communication, as defined here, is a service which could provide the capability to transfer the information between three or more different hosts. Network communication is one of the essential features in MRS since the need for different robots to work cooperatively and the information exchange between different robots. In other words, the network services facilitate different robots to establish the interconnections instead of to be operated individually. A very fundamental problem for network communications is the medium sharing issue. A couple of techniques have been developed, for example, channelization, Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA). For a distributed control scheme, a static medium access control technique like channelization is not enough. The communication of information has to be more dynamic. A packet switching or virtual circuit method is usually considered. This chapter introduces the concepts and developments for the network communications.

An understanding of the evolution of network developments could highlight the possible issues and functionalities during the developments of a network communication environment. Some existing works will also be referenced in this chapter. For instance, the layered network concepts and necessary features for the Ethernet like requests of retransmission could also be properly applied to any specific MRS communication though the existing protocols may not always proper under all the circumstances.

Therefore, an introduction to the history of the network developments will be helpful to identify the network communication problems. Moreover, in order to structure and simplify the various problems, the layered architecture for the network is an effective manner to organize the functionalities for network. Therefore, a brief introduction of Open Systems Interconnection (OSI) model for discussing different functionalities of network communications will be presented in this chapter. Along the network developments, an assessment of the network performance would also be analyzed. Some measurements to properly address the performance of the network are included in the last portion of this chapter.

2.1 Evolution of Network Communications

Classical network communications, including the telegraph and telephone services, are developed to transfer the information in text and voice. However, with the rapid growth of semiconductor technologies, information processed by computers increase exponentially. Modern network communication regarding to the computer data transfer, is then developed on the basis of the classical network communication techniques. The research objectives of this thesis are to implement a simplified and optimized network design for the computer network communications. So the evolutions of the network communication are important references for such purposes. Alberto Leon-Garcia and Indra Widjaja [18] separate the network evolutions into three phases: message switching, circuit switching, and packet switching. A brief overview for the classical communications is mentioned here.

2.1.1 Message Switching

The most original network communication is implemented by the message switching method. Long distance communication is relied on the messenger travels through different locations by feet, animals, or other manners. The communication is fairly slow and unreliable for the manual message switching. In 1837, the telegraph service was first demonstrated by Samuel B. Morse as a practical communication of text messages over long distance. The message was encoded by the Morse code (see Table 2.1) with a combination of lines and dots. The transmission is made by sending electrical current over a copper wire. The messages could therefore be transmitted almost instantaneously from node to node. A well trained human operator can transmit 25 ~ 30 words/minute. Meanwhile, a message routing is still made by human decision according to the destination of messages.

Table 2.1 Morse code.

A	· –	J	· – – –	S	· · ·	2	· · – – –
B	– · · ·	K	– · –	T	–	3	· · · – –
C	– · – ·	L	· – · ·	U	· · –	4	· · · · –
D	– · ·	M	– –	V	· · · –	5	· · · · ·
E	·	N	– ·	W	· – –	6	– · · · ·
F	· · – ·	O	– – –	X	– · · –	7	– – · · ·
G	– – ·	P	· – – ·	Y	– · – –	8	– – – · ·
H	· · · ·	Q	– – · –	Z	– – · ·	9	– – – – ·
I	· ·	R	· – ·	1	· – – – –	0	– – – – –

In order to increase the transmission rate for the telegraph, a technique called multiplexing was then introduced. Multiplexing is the attempt to combine the transmitted information over a single telegraph wire. It is also an initial attempt to share medium on the electrical signal transmission. The Baudot system is developed and adopted in 1874 as the first multiplexing system. Baudot system used five binary symbols as a character. The encoding system further evolves a modern alphanumeric expression ASCII code (American Standard Code for Information Interchange). The table of ASCII code is shown in Table 2.2.

The multiplexing can be realized by signal modulation. The modulated signal carries different sinusoidal signals at different frequencies. The binary information could be transmitted at a pair of frequencies, for example, f_0 as “0” and f_1 as “1”. So by using different pairs of frequencies multiple signals could be transmitted simultaneously. This technique is also known as Frequency Shift Keying (FSK) as a modern communication modulation method.

Table 2.2 ASCII table.

	0	1	2	3	4	5	6	7
0	NUL	SOH	STX	ETX	EOT	ENQ	ACK	BEL
1	DLE	DC1	DC2	DC3	DC4	NAK	SYN	ETB
2	SP	!	“	#	$	%	&	‘
3	0	1	2	3	4	5	6	7
4	@	A	B	C	D	E	F	G
5	P	Q	R	S	T	U	V	W
6	`	a	b	c	d	e	f	g
7	p	q	r	s	t	u	v	w
	8	9	A	B	C	D	E	F
0	BS	HT	LF	VT	FF	CR	SO	SI
1	CAN	EM	SUB	ESC	FS	GS	RS	US
2	(	)	*	+	,	-	.	/
3	8	9	:	“	<	=	>	?
4	H	I	J	K	L	M	N	O
5	X	Y	Z	[	\	]	^	_
6	h	i	j	k	l	m	n	o
7	x	y	z	{	|	}	~	DEL

2.1.2 Circuit Switching

The telegraph service successfully solves the huge propagation delay of the traditional communications. However, the manual routing of information still limits the network communications because of the efficiency and reliability. In 1876 Alexander Graham Bell developed a device to transmit the voice signal. A bidirectional, real-time transmission of voice signal is called telephone service. The telephone service is an analog transmission system compares to the telegraph service as a digital transmission system. The telephone service is convenient and could be operated by the users with little training. This important characteristic quickly leads to the exponential growth of the telephone service.

Nevertheless, a problem was recognized very soon after the number of users grew. The telephone service requires a dedicated line between two users. A network of the telephone service with n users needs $n(n-1)/2$ dedicated lines, which makes the cost significantly increases. Therefore, in 1878, the telephone switches was introduced to reduce the number of dedicated lines by having operators manually establish the connections based on user's demands. Figures 2.1 (a) and (b) show the differences between the networks connections mentioned above.

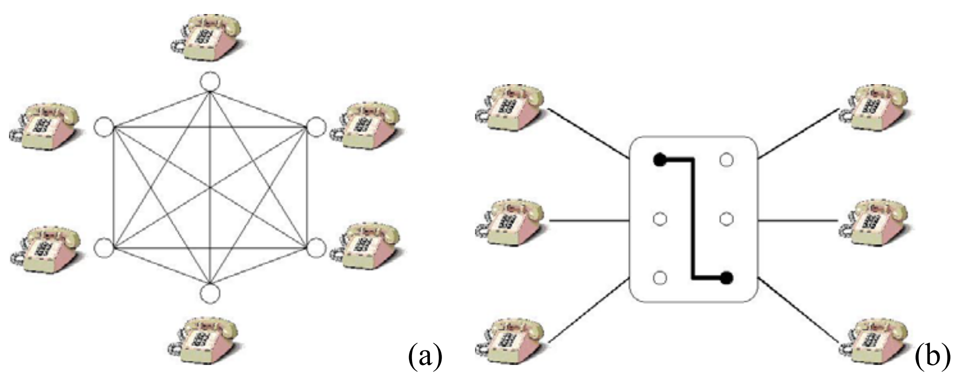


Figure 2.1 Telephone network connections. (a) without circuit switching, and (b) with circuit switching.

With the development of electrical switches, a hierarchical decimal telephone numbering system was developed later for the dialing connection in the telephone network for the compatibility of the large number of users. One of the important features with the telephone network is called connection–oriented because a proper setup is required before the information can be exchanged. This communication procedure is also called circuit-switching. The connection can be separated into three phases within a phone call. In the first phase a connection request sent by the user and proper set up needs to be accomplished. The second phase is the actual transfer of voice from end to end. Finally the third phase is the release for the connection. However, for the circuit switching, the routing decision is made while establishing the services. So the routing information is not needed after the connection has been set up in this situation.

2.1.3 Packet Switching

The message and circuit switching is frequently used by the classical communication systems. However, they both have their deficiencies. The circuit switching improves the efficiency of traditional manual message routing, but it is initially designed for analog information transmission. The occupation of the dedicated lines will also decrease the efficiency of transmission in a network. Meanwhile, the development of computer technology after 1940s largely increases the capability of the information process. So the need for a discrete data transfer in a more dynamic system is requested. The modern communication network was developed on the basis of such a communication manner.

The developments of computer networks were initiated for the military purposes. The first wide geographical area network, Advanced Research Projects Agency NETwork (ARPANET), was developed by Defense Advanced Research Project Agency (DARPA). ARPANET is the ancestor of the Internet. A discussion on the history of Internet can be found in [20]. A critical concept before the implementation of computer networking is packet switching. It is the fundamental principle of the Internet. The packet switching is somewhat similar to the message switching, however information transmitted is cut into separate short segments. There are two types of packet switching: virtual circuit and datagram. The virtual circuit requires the connection of two end nodes to be set up before the actual transmission, and the route of the transmission is fixed during the session. This can guarantee the frames received in order and less overhead is required in the frame. The most common examples are the ATM and X.25. Nevertheless, for datagram transmission, each packet is treated as an independent entity, and full information for the recipient is included in the header of a frame. The frames received at the end point might be out of sequence because of their various routes. The example for datagram transmission is Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). The transmission methods for message switching, circuit switching, and packet switching are shown in Figure 2.2.

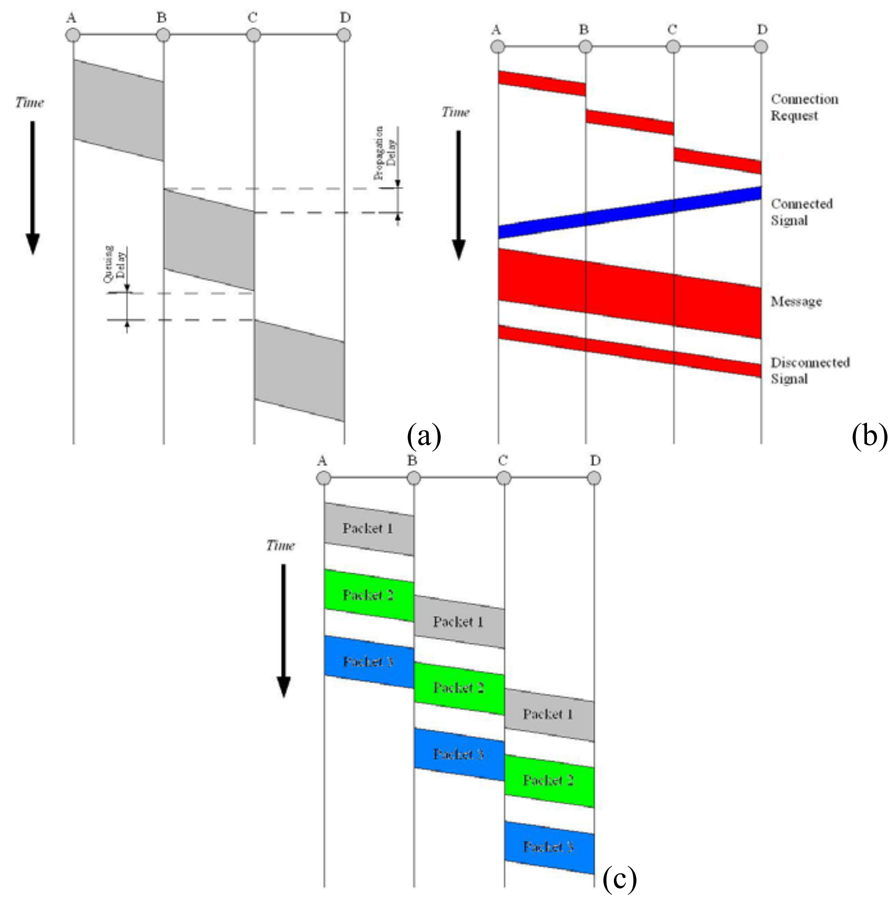


Figure 2.2 Network Switching. (a) message switching, (b) circuit Switching, and (c) packet switching.

2.2 Layered Architecture

With the growing scale of the networks, the increasing need for switching message leads to the further development of layered networks. Different functionalities are regulated at each layer. The proper effort is made for the definitions and reorganization of network services based on such an environment. The network architectures developed by different vendors varied in the early designs. However, the compatibility between different networks begin to attract more and more concerns. A regulated reference network model can also help to bridge different network environments. This section will discuss briefly on the developments of the layered networks. Two most frequently mentioned models are introduced here: OSI model and TCP/IP structure. The similarities and differences between these structures will be highlighted.

2.2.1 OSI Reference Model

The OSI reference model is developed to provide the needs discussed above. The effort is made by International Organization for Standardization (ISO) to provide a reference model for Open Systems Interconnection (OSI). OSI reference model regulates the functions for networking to seven layers in a stack. Each layer only utilizes the services in the lower layers and provides the higher-level features to the upper layers. Figure 2.3 shows the relative position of each layer in the model stack and how each layer can interact with the others.

In Figure 2.3, process in each layer on different machine communicates directly with its counterpart by Protocol Data Unit (PDU). A header contains protocol information and user information is encapsulated with the data provided by the upper layer for each PDU. It is the dialog across the peer processes in the parallel position. However, in order to support such a parallel communication, each lower layer will received the entities called Service Data Unit (SDU) from the upper layer and encapsulate the SDU with its header as the supporting information for the operation in this layer. This is a vertical communication between layers.

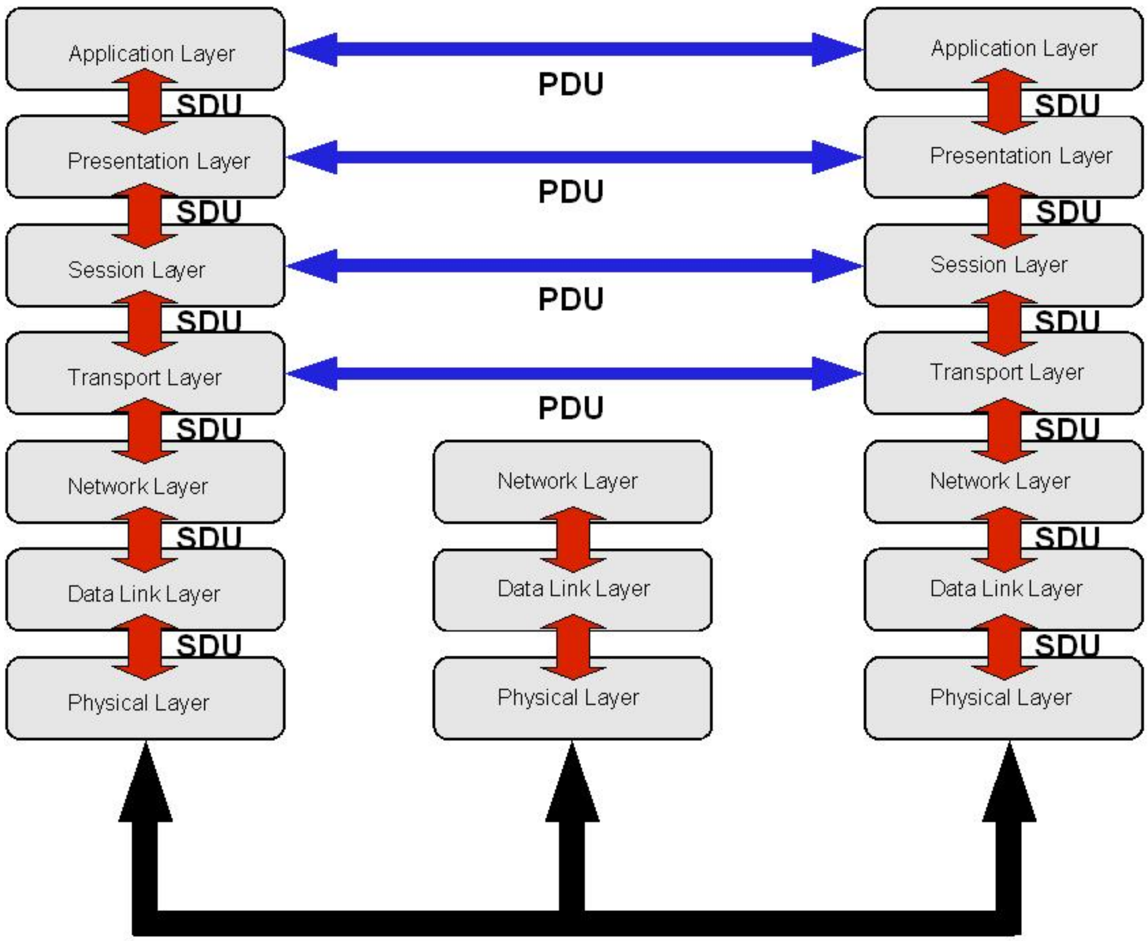


Figure 2.3 OSI reference model.

The OSI reference model is a framework for any further developments on the protocol set for different environments. The descriptions about the seven layers are listed below:

- Physical Layers

The physical layer is responsible for the low level transmission of each bit of the data. It includes all the electrical and mechanical hardware specifications for the transmission of signals. The wire materials, connection interfaces, radio frequencies, and signal modulations are all specified with in this layer.

- Data Link Layer

The data link layer provides the transfer of frames between two different nodes. It includes the procedure to transfer the information by blocks, indicates the boundaries of each frame. Usually the information encapsulated into the frame in the data link layer includes the flow control and addressing information, as well as the cyclic redundancy check bytes. The correction of transmission error within the frame is upon these additional bytes. The error correction is especially important for a high transmission error environment. The flow control and address provides the functions such as Medium Access Control (MAC) so the share of medium could be handled.

- Network Layer

The transmission of information through one host to another host over one or more networks will be handled in this layer. Usually a hierarchical addressing scheme is used to transmit the information over the global network. Appropriate routing services are also provided here in order to deliver the packets from the original network to the destination network. The routing protocol is also responsible for the determination of the optimal path for packet transmission in order to mitigate the congestion and obtain better transmission efficiency. The error control is provided in this layer as well. Unlike the address in data link layer, which is a hardware-based identification, the address for this layer is a logical address. The network layer offers a broader coverage over global network.

- Transport Layer

The transport layer is responsible for end-to-end transfer of data. The segmentation and reassembly of data from upper layers is processed in this layer. The connection between two ends is set up in this layer as well. Besides, the Quality of Service (QoS) is also provided here based on different connection requirements in order to provide the communication in a more reliable or cost effective mean.

- Session Layer

The session layer manages the manner for end user to exchange information. For example, a half duplex dialog or full duplex operation can be assigned here. Other functionalities like checkpointing, adjournment, termination and restart procedure are also offered in this layer.

- Presentation Layer

Presentation layer is in charge of the encoding methods for data from the application layer. The machine dependent codes can therefore be converted into machine independent codes. For instance, an ASCII coded file can be converted into an EBCDIC coded file. Different data encryption schemes are offered here as well.

- Application Layer

The codes and protocols used in this layer provide various communication services. For example, File Transfer Protocol (FTP) provides the service for file transfer. HyperText Transfer Protocol (HTTP) enables the access of World Wide Web (WWW) documents. Other services offered in the application layer include virtual terminal (TELNET), name management (DNS), and mail exchange (POP) (See Appendix A).

2.2.2 TCP/IP structure

OSI reference model has presented a well regulated framework of the layered network structure. The model regulates all the functions and procedures of the network communications. However, it is a quite conceptual network model. A set of protocols to allow physical network communication under OSI reference model is still required. TCP/IP structure is developed by DARPA research project to connect the networks from different vendors to provide several fundamental services over a wide area network. It later becomes a very successful network structure worldwide. In this section, a brief introduction about TCP/IP structure is discussed as an example of network developments under OSI reference model.

TCP/IP architecture usually contains 4 layers: application layer, transport layer, internet layer, and network layer. The mapping between OSI model layers and TCP/IP structure layers is in Figure 2.4.

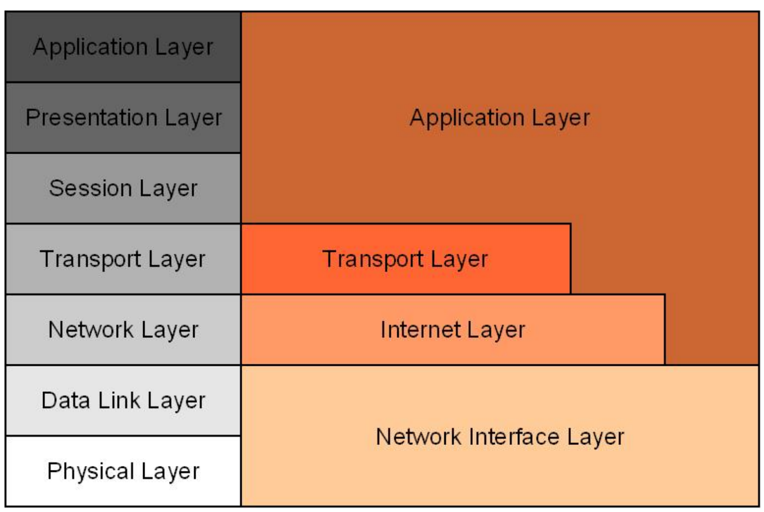


Figure 2.4 Comparison of layer definition between OSI model and TCP/IP structure.

From the figure above, it could be found that the upper 3 layers in OSI model are concluded in the application layer in TCP/IP structure. The transport layer usually contains two major protocols: TCP and UDP. TCP provide a more reliable mean to transfer packets. Also error recovery and flow control is allowed by TCP. UDP, however, is a connectionless way to send packets. It is a less reliable but cost effective way to transmit data. The Internet layer is the same as network layer in OSI model. It is mainly responsible for packet routing. The network interface layer covers the physical data transmission over various hardware interfaces. However, in TCP/IP structure, layers are not as strictly defined as in OSI model so application layer is allowed to bypass the intermediate layers and directly send data units to network interface layer.

As mentioned in OSI reference model. When the data units are passing to the lower layers, each of them will be encapsulated with some extra information regarding to functions in each layer. Appropriate operation could therefore be performed during the delivery of packets from one host to another, and from one end to another end. For example, as in Figure 2.5, the application data like HTTP or FTP request is first sent to the transport layer. The header depending on the service established (TCP or UDP) will be given in front of the application data unit. The encapsulated data unit would then be forwarded to the Internet layer, an Internet Protocol (IP) header will again be attached with the data unit in order to assign destination of the data unit. Before the frame is actually transmitted, the Ethernet header and error checking code will be combined at the front and end therefore the frame could be delivered to the next node correctly. An inverse process will be performed at each of the intermediate node to deliver the information correctly to its destination. Appropriate packet rearrangement and request of retransmission of the lost or error packets will also be handled in order to guarantee the correctness of the data transfer. The documents regulates the formats of TCP, UDP, and

IP headers could be found in [19], [21], and [22]. Other protocols regarding to different services like Real Time Protocol (RTP) could also be found in other relevant RFC documents. Moreover, except for the network protocols developed by DARPA, more network protocols have been developed by various vendors. Table 2.3 lists some of frequently used network protocols for each of the OSI layer.

Table 2.3 List of network protocols.

Layer	Protocols
Application Layer	HTTP, FTP, SMTP, RTSP, POP, TELNET
Presentation Layer	SMB, XDR
Session Layer	SSH, NetBIOS, ASP
Transport Layer	TCP, UDP, RTP, ATP
Network Layer	IP, IPv6,DHCP, ICMP, X.25
Data Link Layer	ARP, RARP, DCAP, IEEE802.11
Physical Layer	T1, encoding methods, signal modulation/demodulation

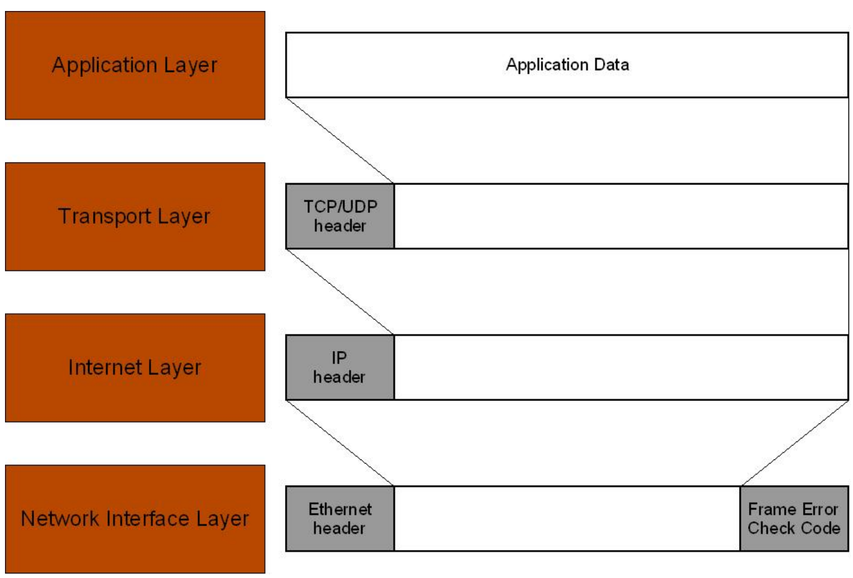


Figure 2.5 Encapsulation of header and error check code into data units.

2.3 Wireless Communications and Issues

The early developments of the network communications are mainly developed for the wire-based environments. Not only because the wire communication is more friendly for signal transmission but also much simpler and secure. However, the wires significantly restrict the mobility of the network communications and applications for communication. With the advances in computer technology, the need to use the electrical mobile devices increases drastically. Mobile devices like laptops, PDAs and cellular phones, as well as the mobile robots and satellites, are required to communicate with each other wirelessly. Also, various industrial and military applications have immense needs to send information without using wires. Therefore, the wireless communication has become a big step in network communications.

The media used for wireless communications are typically radio, or sometimes optical signals. By using the modulation/demodulation methods on these signals, binary data could be transmitted over the air. The wireless communication could hence be implemented. Morse code has also been used extensively for manual operation using radio transceiver in early times. It played an important role for military communications during World War I & II. However, although both wired and wireless communications need to modulate and demodulate the signals, there are still some considerable fundamental differences between them for reasons mentioned in the following:

- Wireless signal is susceptible to noises and Electro-Magnetic Interferences (EMI). A higher error rate is expected in wireless communications.

- Wireless signal strength varies greatly from both different positions and time instants because of the EMI and the multi-path propagation. Transmission collision is hence difficult to be detected under wireless environment.
- The spectrum of wireless signal is restricted comparing to the wired signal. So communication bandwidth and rate are limited and slower.

The differences between wired and wireless network communications are mainly in physical layer and data link layer in OSI seven-layer model (or network interface layer in TCP/IP structure). The upper layer protocols are mostly compatible in both network environments. In the following sections, some discussions will be made about the specific issues related to the wireless network communication. It also plays a very important role in the wireless network design for multi-robot testbed later.

2.3.1 Medium Access Control Protocol

One and maybe the most significant influence of the wireless communication is the medium sharing technique. When two or more devices need to share the same medium for communication, a proper procedure needs to be followed in order to transmit and receive the data correctly in each session. The medium sharing techniques are defined in the network layer in OSI model as MAC protocols. The wired network communications uses collision detection to avoid the collision of transmission between multiple machines. However, since the transmission of wireless signal is susceptible to EMI and multi-path propagation, collision detection becomes impractical to implement. Therefore, the collision of packet transmission needs to be avoided in advance of the actual data frame. This technique is called collision avoidance.

A widely used medium sharing protocol for wired network communication is Carrier Sense Multiple Access with Collision Detection (CSMA-CD). As shown in Figure 2.6, when $t = 0$, host A starts to send a frame to host B while it detects no activities over the medium. After a short period of time t_1, host B also transmit a frame to host A. The transmission frames from both nodes collide at $t = t_2$. Because of the abnormal voltage from the frame collision hasn't reach host B, the medium status for host B is still available. After the propagation time t_{prop}, the transmitted frame from A reaches host B therefore collision has been detected by host B. Also, when $t = 2t_{prop} - t_1$, another transmitted frame also reaches host A so both hosts can detect that collision has occurred. After the collision has been detected, appropriate strategies will be applied in order for frame retransmission. Either the persistent scanning for the availability of the communication channel or the back-off algorithm for rescheduling a retransmission will be performed.

However, the detection of the signal abnormality is not practical for wireless signals due to the significantly variant in magnitude and low Signal to Noise Ratio (SNR). Moreover, the radio transmission has the uneven signal coverage issue. It is called hidden terminal problem as shown in Figure 2.7. Both of node A and C have only the limited signal coverage to the intermediate node B. Therefore, the transmission from either node A or C can't be detected by each other hence the collision can't be avoided by the CSMA-CD method.

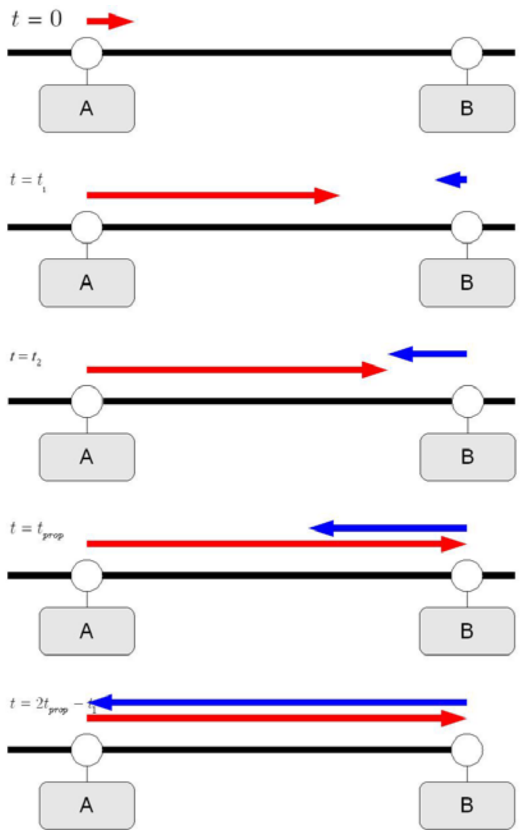


Figure 2.6 CSMA-CD.

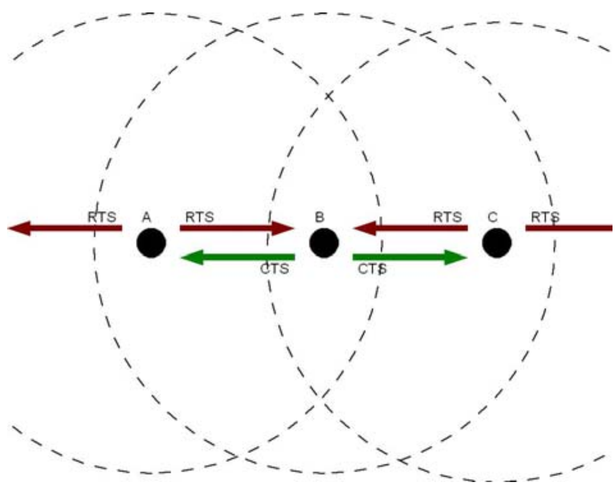


Figure 2.7 Hidden terminal problem for wireless network.

Therefore, instead of sensing the collision of transmitted frame, a more conservative strategy must be applied for an effective medium sharing. In IEEE802.11, a modification is made for CSMA-CD. In order to prevent the data frame collision, a short signal for flow control is sent in advance. When the collision happened to such a request, no response will be answered for the transmission request therefore the collision for data frame could be avoided. This technique is called Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA). It is shown in Figure 2.8.

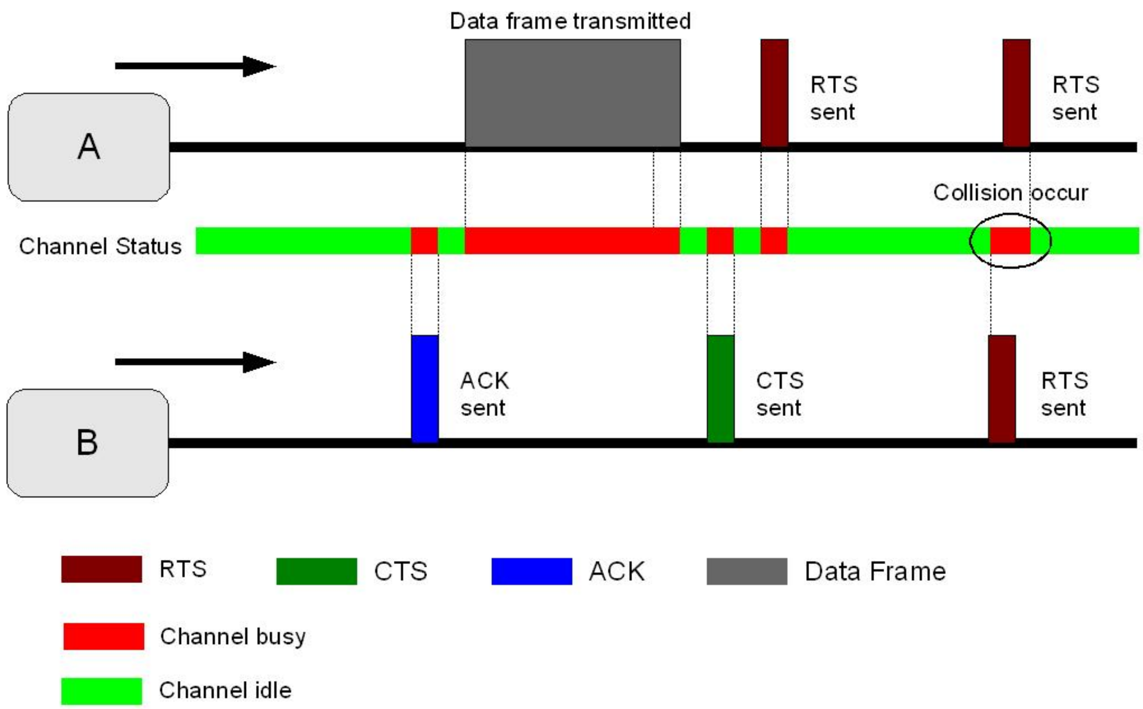


Figure 2.8 CSMA-CA.

Figure 2.8 shows the occurrence of the collision and how data frame is transmitted. In the beginning both channels attempt to transmit Request-To-Send (RTS) signal. The collision happens and therefore both hosts A and B will not response to the request. A back-off algorithm is applied on both hosts. After the waiting for a shorter back-off period, host A attempts to re-transmit the RTS frame and seize the control of the channel. Host B responses to host A with a frame Clear-To-Send (CTS) after RTS frame is received. The data frame is hence sent from host A to host B after RTS is recognized. With the time elapse during the data transmission, all of the other host will remain silent so the period is collision free. The channel will become available again after the transmitted data frame is confirmed by sending the acknowledge frame ACK from host B.

2.3.2 Ad hoc and Infrastructure Topology

Another important aspect for wireless networks is the network topology. The wireless network has great mobility comparing to the wired network. Therefore it has been vastly used on mobile devices. As a result, the dynamic reallocation of the network nodes leads to the requirement for more dynamic connections in the network. Traditional network topologies for wired network communication are somewhat restrictive in such an environment. In this section, the network interconnections and developments for the dynamic topologies will be briefly introduced.

The interconnections betweens network nodes in a network could be divided into two categories: physical connection and logical connection. Physical connections means two nodes are locally connected to each other by physical hardware such as Network Interface Card (NIC), cables, switch or router. It is a hardware based connection. Logical connection means two network nodes are linked to each other by various network protocols as they are in the same network (LAN). It is a software oriented manner. Two or more nodes at different geological locations could logically be located in the same network. Protocol such as Virtual Private Network (VPN) is an example to provide a logical connection. Various wired network topologies could be found in Figure 2.9. The links could be either physical or logical.

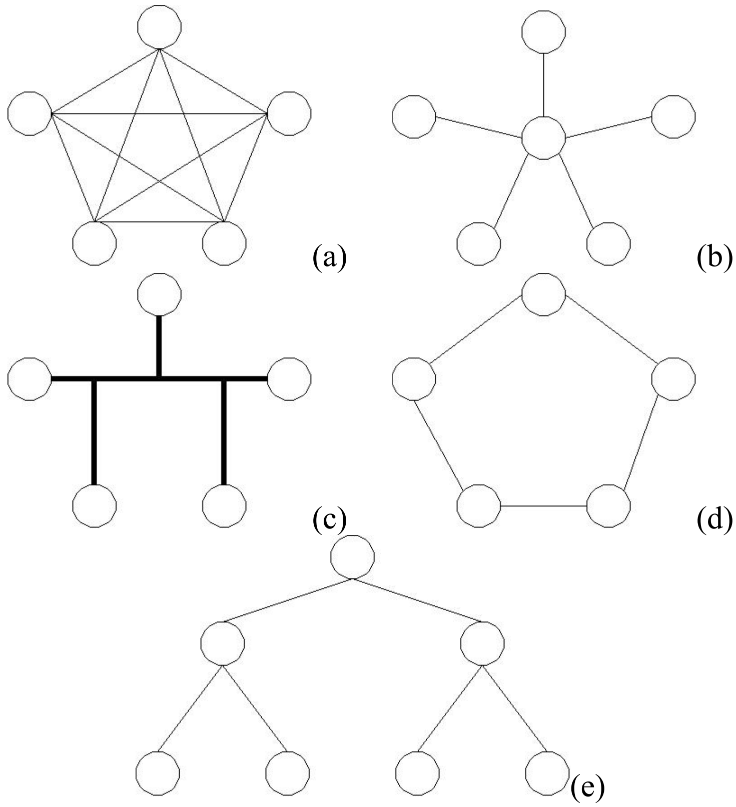


Figure 2.9 Network topologies. (a) mesh topology, (b) star, (c) bus topology, (d) ring topology, and (e) tree topology.

The traditional network topologies are basically the centralized architectures. All the packets usually won't be transferred directly between two nodes. The transmission is centralized so all the packets will be sent to a leading node as the network hub first. However, for the wireless mobile environment, the communications sometimes need to be performed in a decentralized mode when the global signal coverage for the hub is not possible. Instead of using any fixed network topology as either one in Figure 2.9, the network topology is required to be more dynamic. Therefore, the network topology ad hoc mode has been used in the wireless mobile communication environment. In ad hoc mode, transmission could be performed between different nodes directly without using an intermediate access point. It is also known as peer-to-peer network. Moreover, this peer-to-peer network topology is mostly used for mobile wireless network. Therefore, sometimes it is known as the Mobile Ad hoc NETwork (MANET). The official charter for MANET could be found in [23]. The MANET is usually implemented under the environment with following characteristics:

- The network topologies could change rapidly and unpredictably.
- The network is decentralized and lack of prefix allocation agency.
- The devices running in MANET are usually power limited and equipped with lower processing capability.

The MANET provides the network some advantages such as the scalability, mobility, and dynamic communication environment. It could solve the issues when the reallocation for network nodes occurred frequently. However, the MANET is still under development. Only a few experimental network standards have been proposed for MANET. These standards mostly provide packet routing services. Some reference documents for experimental packet routing protocols can be found in [24] ~ [27]. There are still a number of technical challenges that needs to be overcome such as addressing, packet routing, network security, and QoS for MANET. Also, characteristics for different types of network links such as standalone ad hoc network or hybrid ad hoc network could vary greatly. Nevertheless, MANET could provide a quite attractive communication solution for the wireless multi robot systems. In addition, the communication network proposed in this thesis is a simple experimental network for a semi-MANET communication environment.

2.4 Communication Performance

Another important aspect in order to understand the network protocols is the analysis for the communication performance. Performing such an analysis could provide a better understanding for the network capability and reliability. Any revision for the existing protocols in order to improve the network performance could also be verified theoretically due to such analysis. In this section, some of the fundamental network measurements will be briefly discussed. More terminologies about some concepts of the network performance factors could be found in [28].

2.4.1 Bandwidth

For the communication terminologies, this term is obscure. It has two different meanings. The first definition is the width of the band of frequency used to carry data. This will usually affect the communication rate since the carrier with higher frequency has larger density for data. For example, the bandpass communication is usually faster than the baseband communication. However, the concept addressed here is the second definition, which is the communication rate for data transmission over physical carrier. This is determined in the physical layer. Different modulation/demodulation techniques, hardware specifications and signal carriers used decide the maximum capability of the transmission. For example, the maximum bandwidth for the traditional dialup network using MODEM over the phone line is usually 65536bps. The bandwidth for IEEE802.3u is 100Mbps. The bandwidth for IEEE802.3ae is 10Gbps. The protocols adopted in the upper layer will not have any influence on the communication bandwidth.

2.4.2 Transmission Loss

The transmission loss will deteriorate the actual transmission rate and quality. It occurred for various reasons from hardware based factors to protocol based factors. For instance, a low SNR environment could lead to a higher transmission error. This usually results from either longer transmission distance between relay nodes or low quality transmission medium (higher EMI or worse cable quality). Also, the protocols adopted in the network design could also have impact on the transmission error. The more bits contained in each individual frame, the more possibility for a transmission error could occurred within a frame. Too much routing could also make the transmitted packet to be obsolete. Two different circumstances will happen as the transmission loss: frame loss or frame error. When a frame is lost during the transmission, no response for the frame acknowledgement will be received therefore it could be detected. On the other hand, the frame being received incorrectly could be found by the Cyclic Redundancy Check (CRC) code attached at the end of each frame or packet. When either of the communication abnormalities happened, an appropriate arrangement for re-transmission will be made so the problem could be corrected. The protocol used for frame re-transmission is called Automatic Repeat reQuest (ARQ) protocol. Three different types of ARQ protocols are used for frame re-transmission: stop and wait ARQ, go-back-n ARQ, and selective repeat ARQ. Different efficiencies and computational requirements are needed for different ARQ protocols. The details for ARQ protocols used will be further discussed in chapter 4.

However, the efforts to guarantee the data is being transmitted and received correctly usually need more overhead, which cause a lower effective transmission rate. Some tradeoff must be made between the quality and quantity for communications.

2.4.3 Throughput

The communication bandwidth couldn’t present the actual communication rate for user data. The transmission loss, repeat request, and the wait for establishing the connection could all reduce the rate. Therefore, the network throughput makes more sense to present the real communication performance. According to the definition in [28], the network throughput is defined as “the maximum rate at which none of the offered frames are dropped by the device”. The throughput of a network is mainly determined at lower layers (physical layer, data link layer, and network layer). The factors which have influences on the throughput include ARQ protocols, MAC protocols, network congestion and packet routing protocols.

2.4.4 Latency

One of the very important issues for network performance is the latency. It is defined [28] as "the time interval starting when the last bit of the input frame reaches the input port and ending when the first bit of the output frame is seen on the output port". The network latency also represent the time it takes from the time data is requested to the time it is arrived. Sometimes, it is also used to define how much control we have for the network. Not only the latency but also the jittering, which is the variation of the latency, are important when we want to measure the performance. It is a fairly critical issue for the distributed control problem or multi-agent systems. One of the methods to mitigate such problem is QoS, which normally reserve certain amount of bandwidth for specific services. Also, a real-time system to guarantee a minimum delay of system operation for MRS is another solution.

In the other hand, the communication performance is also highly dependent on the hardware specifications. The hardware design is another critical point in this thesis. Different hardware architecture has influential impact to the performance on not only communication but also processing and maneuvers capabilities. The next chapter will therefore focus on the hardware specifications and their restrictions.

CHAPTER 3
WIRELESS MULTI-ROBOT TESTBED

As the discussion in the previous chapter, it could be found that the development of the network communications is based on the hardware specifications and mission objectives. Protocols used in the lower layers are highly dependent on the physical signal types and modulation/demodulation techniques adopted by the hardware. Therefore it has become fairly important to understand the physical hardware used for the experimental testbed before the discussion of the dedicated network environment.

Meanwhile, the understanding for the concept of system operation is also critical before designing the network. To appropriately identify the requirements for the system operation is the essential to support the operation of the testbed in a cost effective way. The design of the network protocols for upper layers is mainly determined by the mission requirements. The services provided by the network and their performances are the key factors which lead to a satisfactory network development. Therefore, all the hardware facilities and various sub-systems, for example, positioning system and communication system, will be mentioned in this chapter before the discussion of network protocols.

3.1 Hardware Architecture of the testbed

The wireless multi-robot testbed is composed of several sub-components including mobile robots, positioning system, the operational area which provide the region for its operation. The hardware architecture of the testbed is shown in Figure 3.1. The mobile robot is controlled by the independent controller on each of them. The positioning system determines 3 dimensional positions of the LEDs and orientations of the LED-mounted objects by using eight cameras mounted as shown in the figure. A central computer is responsible to provide information for localizing all the obstacles and moving objects via the communication system. Also any user inputs to command the system can also be transmitted though the central computer. The detail description on each sub-system will be provided in the rest sections of this chapter.

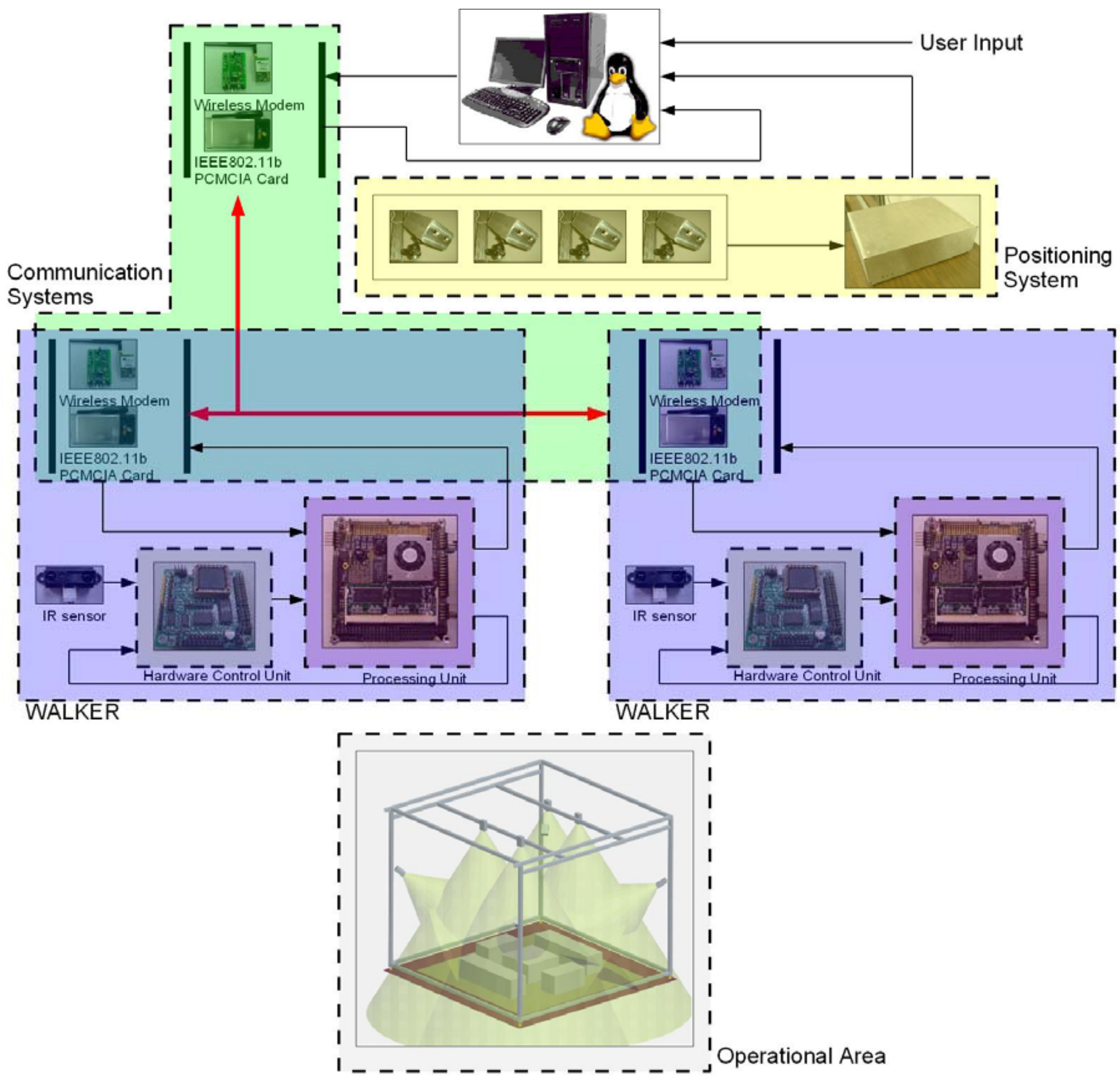


Figure 3.1 Hardware architecture of the testbed.

3.2 Wireless Mobile Robot

The core components for the testbed are the mobile robots, which are considered as intellectual (and autonomous) agents in the system. Due to the physical application requirements, the robots in the testbed must have the following features:

- Mobility

A mobile robot system can be used to validate the concepts and algorithms for path planning, vision servo control, leader-follower problem. It is also widely applicable for many autonomous vehicle control applications. So the appropriate maneuvers to move the robot itself are required.

- Wireless communication

The control of the robot needs the communications. Hence an adequate transceiver to send/receive control commands, transmit all the required information back and forth between different vehicles is needed. However, for a mobile robot, wires could enormously restrict the mobility. Therefore, the wireless communication is the essentials to remove this constraint.

- Decentralized control

A multi-agent system needs multiple processing threads/controllers to control different physical agents. Under some restricted circumstances, a centralized control of multiple robots is not feasible. Therefore, the design of the testbed requires a controller or processing facility on each of the individual robot.

- Scalability

Mobile robot can dynamically change its location, therefore, the fluctuation of the number of robots during the operation is assumed. For many multi-agent systems, the scalability is considered during the operation. So the functional robots in the testbed could be added or removed any time in order to keep the flexibility of the operation.

The robot WALKER is developed here for the MAS research based on the considerations discussed above. The WALKER acronym stands for Wireless Autonomous Linux-based Kinematic Expert Robot. It is shown in Figure 3.2.

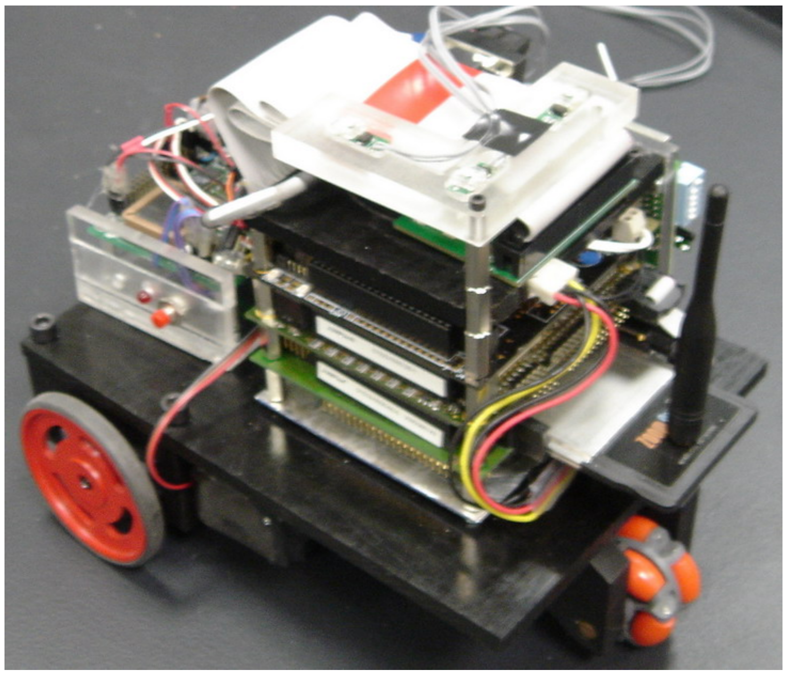


Figure 3.2 WALKER for multi-robot testbed.

The dimension for the WALKER is $8.75'' \times 6'' \times 7''$ ($L \times W \times H$). It is a modulized design comprising various modules so the maintenance could be easier. Also it could be more flexible to any further development since the upgrade of the hardware can be done by simply replacing individual modules. The WALKER has four different modules to support its operation: power module, processing unit, communication module, and hardware control unit. The inter-connections between each module is shown in Figure 3.3. The hardware used for each module will be mentioned in the following subsections.

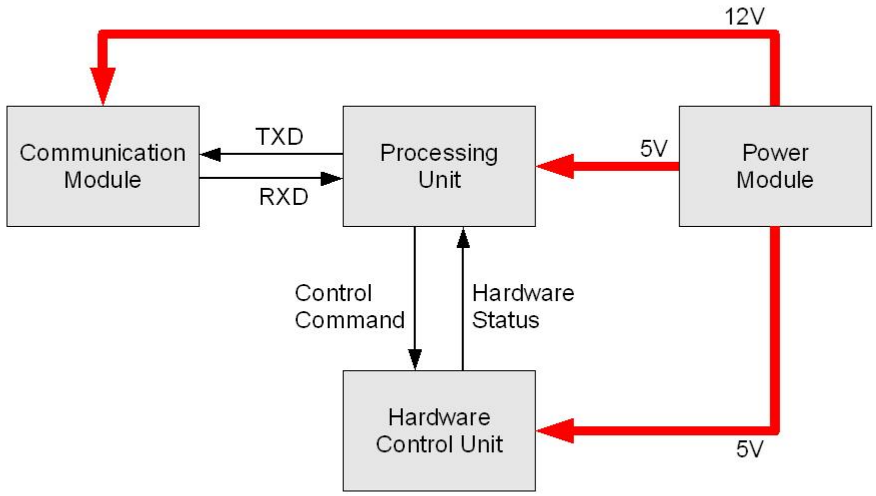
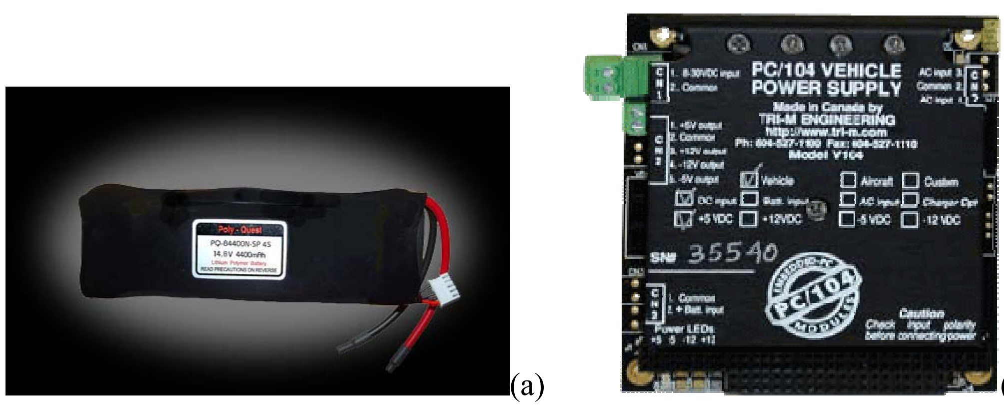


Figure 3.3 Block diagram for modules on WALKER.

3.2.1 Power Module

The power module is composed of a lithium-polymer rechargeable battery and the DC/DC power supply for PC/104. The output voltage for the lithium-polymer battery is 14.8V, the power capacity is 4400mAh. The battery connects to the power supply and converts the power to the regulated 12V and 5V outputs to support the requisite operation on the robot. The pictures for the power module are in Figure 3.4. The power module could support the system operation for roughly 8 hours when the system is idle under Linux.



(a) (b)

Figure 3.4 Hardware pictures for power module. (a) lithium-polymer rechargeable battery, and (b) PC104 DC power supply.

3.2.2 Communication Module

There are two different channels for the wireless communications. The differences for two channels are listed in Table 3.1. However, this thesis only discusses for the low bandwidth communication channel. The reason for this choice will be mentioned in the next chapter. Pictures for the hardware are shown in Figure 3.5.

Table 3.1 Comparison of different communication channels.

	Wireless modem	IEEE802.11b PCMCIA card
Modulation method	FSK	BPSK/QPSK/CCK
Radio Frequency	900 MHz	2.4 GHz
Bandwidth	38400 bps	11 Mbps
Signal range (outdoor/indoor)	300’ / 1000’	300’ / 1000’
Power Consumption	0.225 Watt	1.235 Watt

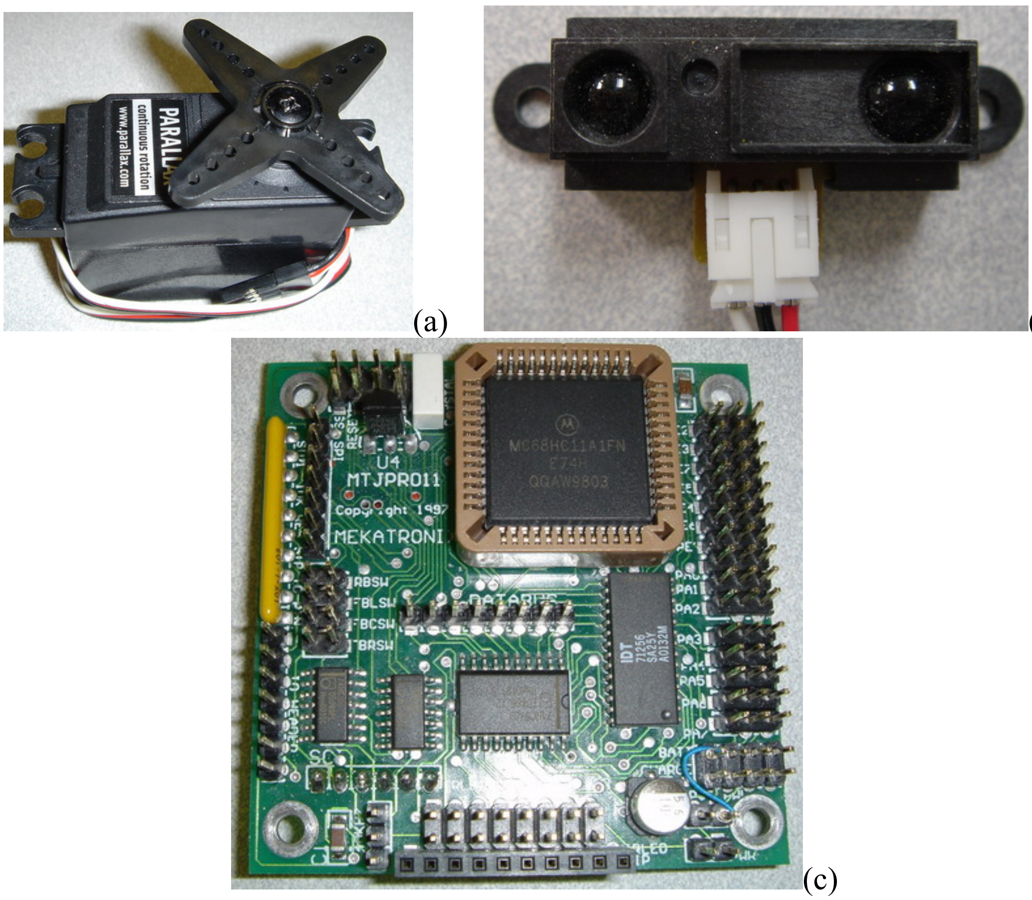

(a)


(b)

Figure 3.5 Hardware pictures for communication module. (a) Low bandwidth channel (wireless modem), and (b) High bandwidth channel (IEEE802.11b PCMCIA card).

3.2.3 Hardware Control Unit

The hardware control for the WALKER contains the controller for motors, input D/A (Digital to Analog) and output A/D channels for various sensors. It is the intermediate interface between processing unit and the physical hardware. The hardware control unit uses a Motorola 68HC11 based board with 32 K SRAM as the controller. The detail reference for the board can be found in [29]. Also, the WALKER currently uses two servo motors to control its motion and a pair of infrared sensors for obstacle avoidance. The servo motor is controller by Pulse Width Modulation (PWM) signals, and the IR sensors needs to be converted by Analog to Digital Converter (ADC). However, more optional facilities like camera and power management system could also be controlled by this module. The pictures for the hardware control unit can be found in Figure 3.6.



(a) (b) (c)

Figure 3.6 Hardware and hardware control unit. (a) servo motor, (b) infrared sensor, and (c) MC68HC11 controller.

3.2.4 Processing Unit

The processing unit is the kernel of the robot. It greatly enhances the capabilities and features for the robot. The processing unit turns the robot into an intellectual and autonomous agent instead of simply a mobile robot. The processing unit is responsible for performing the required computations for control actions and the cooperative behaviors, as well as the requisite network communication with the other agents.

The processing unit uses PC/104 board for the robot. The specifications for the processing unit are in Table 3.2. Figure 3.7 shows the picture of PC/104 module.

Table 3.2 Specifications for processing unit.

	Specifications
Manufacturer / module number	Kontron / MOPlcd6
Processor	Pentium MMX 266MHz
Memory	64Mbytes
Disk	512 Mbytes CF card
Operating System	White Dwarf Linux 2.0

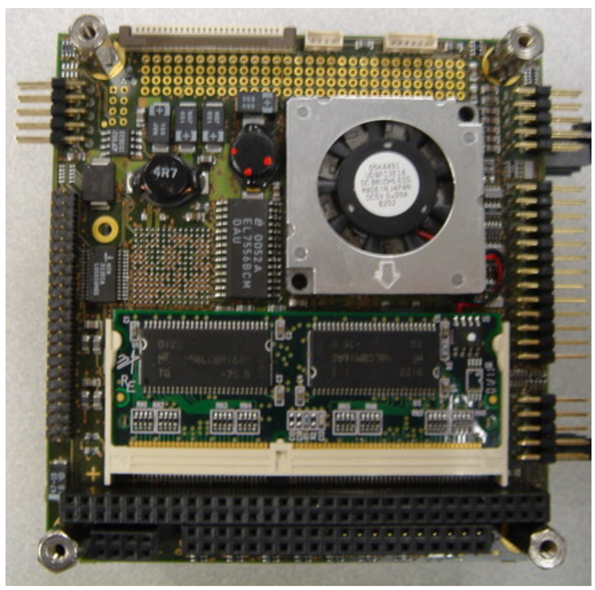


Figure 3.7 PC/104 processing unit.

3.3 Positioning System

The localizations of the mobile robots and all the possible obstacles for many of the multi-robot testbeds are fairly computationally expensive. The onboard camera with the simple image processing technique like feature points extraction is usually required with the sharing of the information between each robots for localization. However, for the wireless multi-robot testbed discussed in this thesis, a computationally cost effective positioning system is used for the localization. The positions for the objects are provided in the system by the PhaseSpace position measurement system. Eight cameras are mounted on the outer aluminum frame in order to cover the whole operational area. The LEDs are required to be attached on the targets so that the cameras can track the positions and orientations of the LEDs and hence the targets. The block diagram of the positioning system can be found in Figure 3.8.

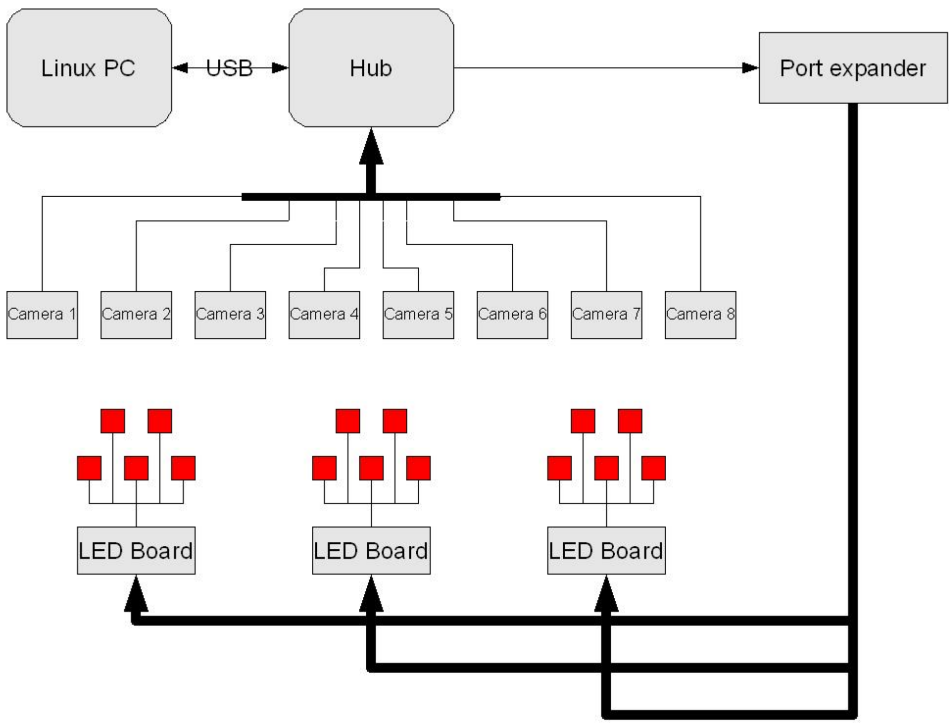


Figure 3.8 Block diagram of the PhaseSpace positioning system.

In Figure 3.8, the cameras are connected to the hub by an USB connection. The PC is running under Linux operating system. Also, the hub has the connections to the LEDs via proper adaptor interfaces. Different LEDs could be recognized by the system by sending the flashing signals at specific frequencies so each LED could be identified with its specific number. The positioning system could generate the 3-D data for all the tracking points at a rate of 220 fps. It is, however, enough for detecting the robot motions.

The pictures of positioning system are shown in Figure 3.9. The detail discussion about the determination of 3-D position of LED under the PhaseSpace system could be found in [15].

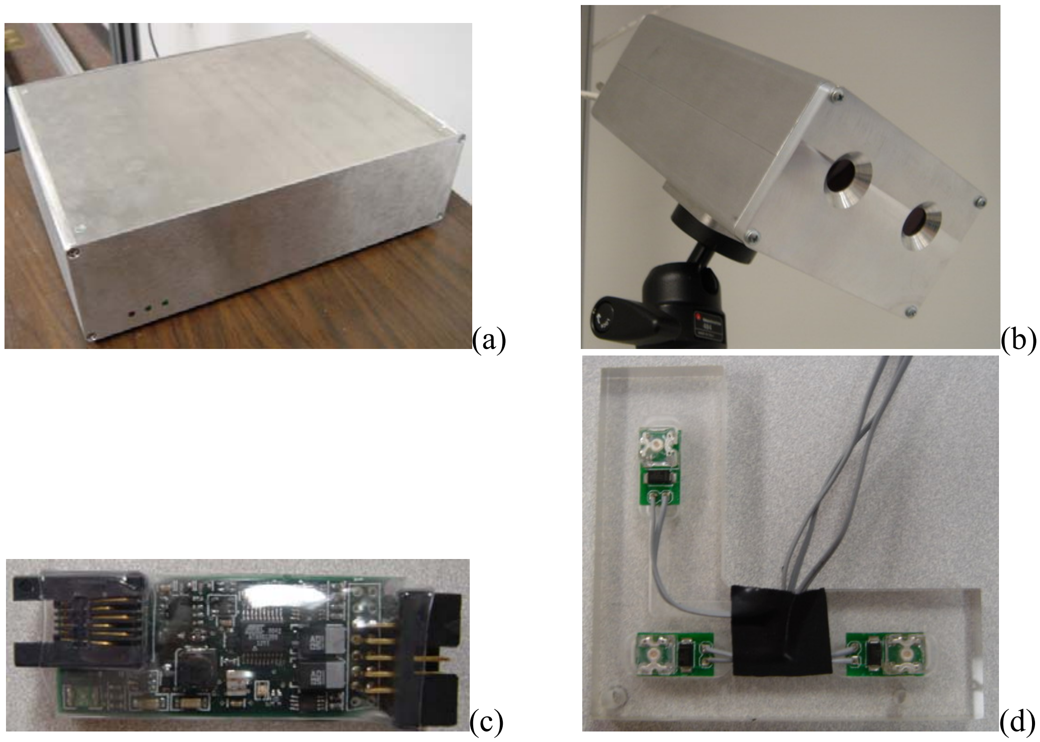
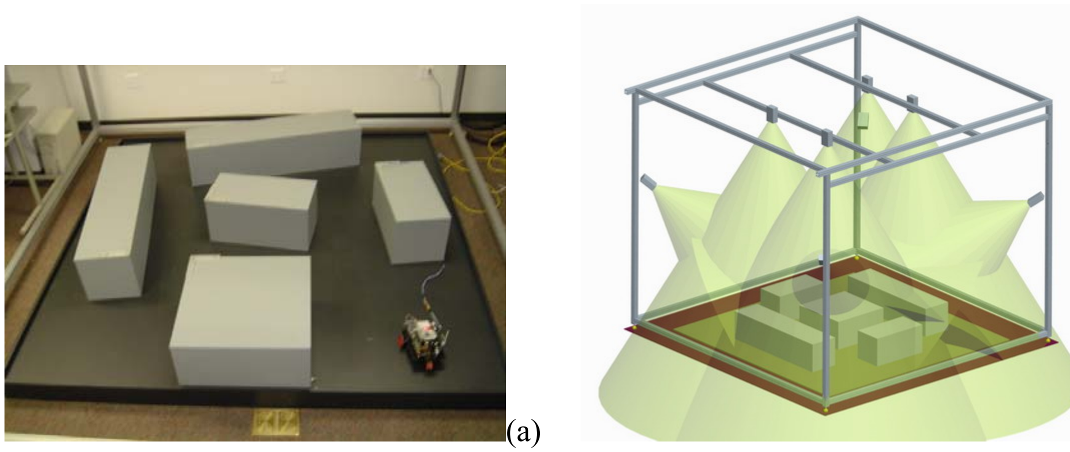


Figure 3.9 Pictures of hardware for PhaseSpace positioning system. (a) hub, (b) camera, (c) LED board, and (d) LEDs.

3.4 Operational Area

By using the positioning system, the objects could be properly located within certain range. However, due to the physical restrictions of the positioning system and available room, the operation can only valid within a limited area. Therefore, in order to enhance the operation of multiple robots and ensure the vehicle operations are valid, a platform is made for restraining the region of the motions and placing the obstacles for different research scenarios. The floor and several blocks used for the platform and obstacles are made of foam. The figures in Figure 3.10 include the geometry of the testbed for the platform, obstacles, and the positioning system.



(a) (b)

Figure 3.10 Geometry of the testbed. (a) positions of the operational area, and (b) projections of the visible range for the positioning system.

From the description in Figure 3.1 above, it could be observed that a communication network is required to support the operation of the wireless MRS testbed by using the communication module mentioned in section 3.2.2. The next chapter will describe a dedicated protocol suite using the low bandwidth channel to enable the inter-cooperation between various robots as different individual agents.

CHAPTER 4
PROTOCOL SUITE

This chapter describes the protocol design for the self-configurable network used for the wireless multi-robot testbed. The network interfaces and protocol suite mentioned in this chapter are the communication implementations on the experimental multi-robot testbed mentioned in the previous chapter. A complete network environment is outlined in this chapter. Some considerations and hardware specific issues are addressed in section 4.1. In order to simplify the communication scenarios and problems, only LAN is considered here. Section 4.2 introduces a dedicated LAN for the testbed. A few of the protocols have been specified for this layered network to perform the operation of the network communications. This will be discussed in detail in section 4.3.

4.1 Limitations and Requirements

Chapter 3 has describes the equipments used in the wireless multi-robot testbed. Before the attention is focused on the design of network environment, explicit statements of the network restriction are provided.

The most important principle for the network design for the testbed in this thesis is the minimal realization for a required network communication with better hardware compatibility. This means the optimization of the use of the onboard resources including the power and computational needs, for example, memory and minimal processor required. In other words, to support the system operation in a more efficient manner in terms of the power and computational uses is the highest design principal.

The first step for the design problem is the understanding of all the constraints and requirements. The limitations of the wireless multi-robot testbed are hence listed below:

1. Power consumption on the mobile robot needs to be minimized. So a transceiver with lower power consumption used on the robot is preferred.
2. Lower bandwidth channel (wireless modem) is the preferred device for the high level data transmission such as a control command because the lower required bandwidth, lower power consumption and better signal sensibility (and reliability).
3. Higher bandwidth channel (PCMCIA wireless Ethernet card) is the preferred device for a low level data transmission such as the image data. A mixed use of both low and high bandwidth channels can make the communication to be more robust and efficient. However, the transmission of low level data is not in the scope of this thesis.

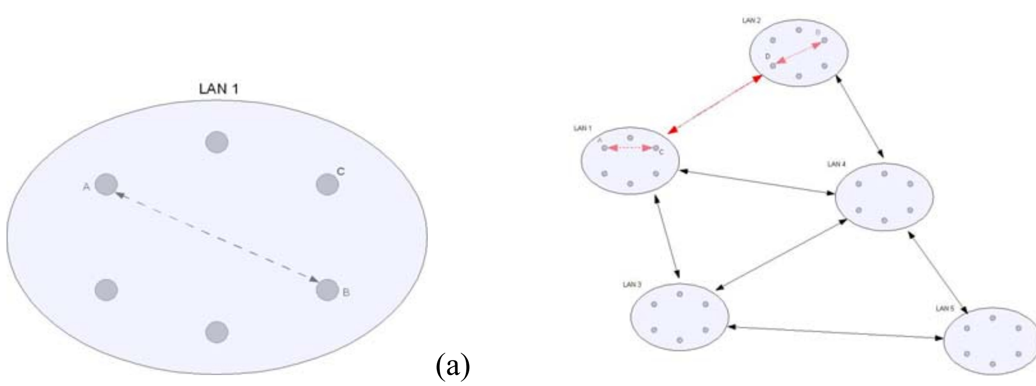
The requirements to support the system operation are specified below:

1. Command refresh rate for mobile robot control could be less 5 Hz since the transient response for a mechanical mechanism is relatively slow. Therefore the data rate of 38400 bps is enough for robot control
2. The operation requires the inter-operation between agents. Therefore the application layer Agent Communication Language (ACL) is also needed to be defined for the network communication to handle the conversation in lieu of simply low level data transmission.

3. The scale of the fleet in the multi-robot testbed is restrictive. Hence in order to simplify the network, only a LAN is discussed here. The packet routing protocol is not under consideration in this thesis.
4. The network topology is comprised of one leader and multiple followers.
5. In order to enhance the autonomous operation and decentralized control, an automatic configuration of the topology is required by the system so the robot doesn't definitely need the command offered from the leader to make such a change. This procedure will be covered in the next chapter.

4.2 Local Area Network Architecture

A very important assumption made here is the scale of network. As the most frequently used topology, the tree topology needs a hierarchical addressing technique and ability to forward the information to its destination. This also includes sophisticated algorithms and protocols for data routing. Therefore, a significant simplification could be made in the design problem by confining the network to only LAN. Moreover, some of the intermediate layers could also be skipped since only a single LAN has been considered here. The difference of the LAN and Wide Area Network (WAN) can be found in Figure 4.1.



(a) (b)

Figure 4.1 Comparison of the interconnections of different networks (a) LAN, and (b) WAN.

As it is shown in Figure 4.1(a), all of the nodes in LAN 1 could be accessed using the local addresses in the LAN. For example, the local address for node A and node B in Figure 4.1(a) are x and y respectively. The two nodes could therefore reach each other by using their local addresses within the same network. The information routing under such case is not going to be required except in the infrastructure mode. The frame transmission from node A to B will go though the intermediate node C as the local network hub under infrastructure mode. Otherwise, no forwarding of information will be required in ad hoc mode under local network.

However, as shown in Figure 4.1(b), the addresses within each LAN are only valid for the other nodes in the same LAN. A direct connection can't be made across different LANs. The only exception is the specific bridges used for interconnection between different LANs. Therefore, in order to have the access for each node in the WAN, a global address needs to be given to each node. Usually, a hierarchical addressing method is considered in this case to improve the scalability of network. For example, a local address for node A in LAN 1 is x and the address for node B in LAN 2 is y. However, since node A and B are not in the same network, they can't reach each other by using their local addresses. The numbering on each of the networks is required to address a global identification. Therefore, as the topology in Figure 4.1(b), a given global address for the node A is $1.x$ and $2.y$ for node B. When the transmission occurred between these two nodes, the information will first be transmitted from node A to the local network leader B, then the received packet will be forward to the other network leader node D in LAN2, another information routing will happened then from node D to node B in LAN 2. As it could be observed here, the addressing is used not only for the medium sharing purpose but also for the information routing. Nevertheless, as it has already been discussed in chapter 2, the data link layer and network layer (in ISO model) are used to handle the problems.

Another critical packet routing issue also happened when signal can't globally cover the physical range of a network. When the communication needs to be made from one node to another node in the network between two far ends, the determination of the forwarding route becomes sophisticated, especially when the network is under ad hoc mode or the hybrid of ad hoc and infrastructure mode. Although the routing protocols for wired network environment are already well developed, the networking in a mixed network environment of different communication modes is still somewhat limited. The proper routing protocol used highly depends on the type of the network environment.

The wireless multi-robot testbed discussed in the previous chapter is comprised of several mobile robots. The number of robots is however limited. Since the objective for the network communication is only for the collaborations between a limited numbers of small robots, a more cost effective manner to implement the network communication here will be to consider the environment to be only a single LAN. Iin the next section, the network and transport layers in the dedicated network are ignored under such an assumption. As a result, both the computational cost and complexity of the network can be significantly reduced.

4.3 Protocol Specifications

The above discussion provides an explicit explanation of the network communication considerations and infrastructure. The detail specifications of the dedicated wireless network are described in this section.

First, the network layers of the wireless communication are shown in Figure 4.2. In Figure 4.2, the protocols include the pre-programmed protocols on the wireless modem and specified protocols. The pre-programmed protocols are hard coded on the wireless modem and the header for the raw transmission frame cannot be accessed. The pre-programmed protocols covers two ISO layers by using Modbus protocol [30] as the data link layer protocols, and a specific protocol [31] for network layer. The network layer protocol using vendor identification number, channel, destination address, and address mask to provide the networking features and filtration. However, the hard coded network layer protocol is basically a Point-to-Point Protocol (PPP) which is designed for a centralized basis communication scenario. As the decentralized communication need, the provided protocols cannot satisfy the requirements for the operation. Moreover, the header for each frame cannot be captured or modified in a software manner. Hard coding the protocols into the firmware on wireless modem provides great convenience for the end user to control various devices using serial port communication. However, the lack of the flexibility with such design method significantly restricts the possibilities for further network programming and control. Therefore, in order to obtain the full control on the robot network communications, the pre-programmed protocols are ignored, and the additional protocols are specified in the thesis instead.

The specified network communication structure contains two layers, data link layer and application layer. As discussed in the chapter 2 for the layering in TCP/IP structure, it is feasible to skip over the intermediate layers and have the network services directly encapsulate the application layer SDU into the data link layer frame. Hence, due to the consideration mentioned in previous section, the global addressing is ignored and the data link layer could have the direct access to the application layer.

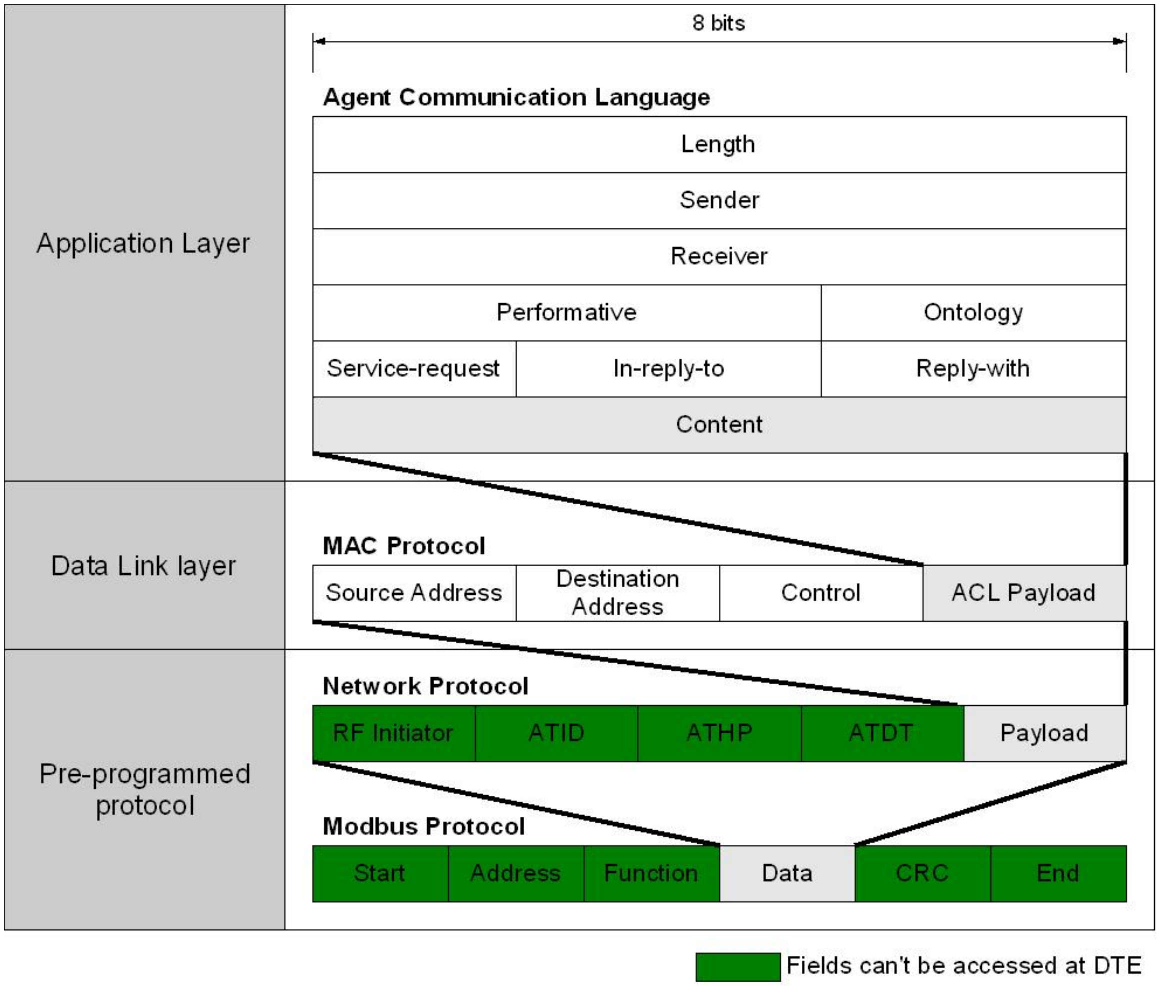


Figure 4.2 Dedicated wireless network layers

4.3.1 Data Link Layer Protocol

The specified data link SDU contains three fields: source address, destination address, control information, and its payload. The purpose of this layer and the frame header is for the medium access and flow control purposes. The design of this frame is referenced from High-level Data Link Control (HDLC). However, the HDLC is also a PPP. Therefore the destination address is added to the frame for the wireless network medium access. The detail explanations for the meaning of each field are defined as below:

- *Source address*

    It is the address or ID for the frame transmitter. This is an 8 bits long field. 255 devices can be addressed.

- *Destination address*

    It is the address or ID for the frame receiver. This is an 8 bits long field. 255 devices can be addressed.

- *Control*

    The control field is responsible for establishing or releasing the connection for data transmission, as well as the functions of the frame retransmission and acknowledgement for the reception of previously transmitted frame. The ARQ protocol is also implemented by the control field. It is an 8 bits long field. The format of this frame is defined in Figure 4.3. The control field used here is similar to the HDLC procedure [32]. Three types of frame are used here: information frame, supervisory frame, and unnumbered frame. Information frame are used for the transmission of datagram from upper layer. $N(S)$ represents the send sequence number for the frame, and $N(R)$ represents the response sequence number. The bit P/F indicates the direction for the data transmission. The supervisory frame is for the flow and error control. The acknowledgement (ACK) frame and negative acknowledgement (NAK) frames could be used to confirm the correctness of the transmission. It comes with only response sequence number at the end since no data is contained in this frame. The unnumbered frame is used to establish or release the connection. Three different modes of connection could be established by unnumbered frame: Normal Response Mode (NRM), Asynchronous Balanced Mode (ABM), and Asynchronous Response Mode (ARM).

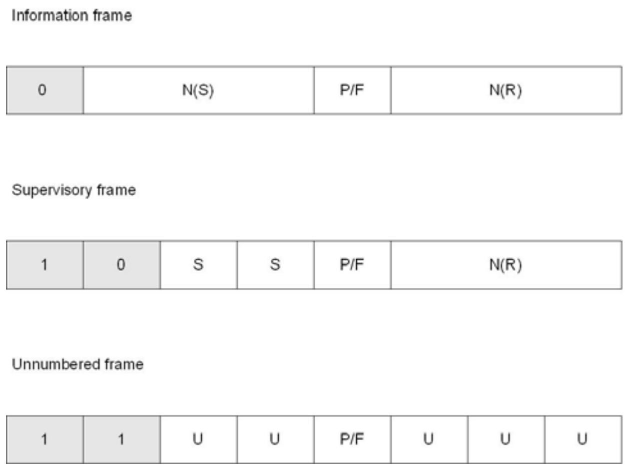


Figure 4.3 Bit-wise format of the control field

4.3.1.1 Link management

The normal response mode is the only mode used here for the network communication. It is a synchronous transmission mode. So the secondary node can only transmit when it is instructed by the primary mode. It is used under the half duplex environment. The transmission mode is less efficient. However, it is computational inexpensive since less buffer is needed and no data rearrangements needs to be made. The transmission procedure for NRM is in Figure 4.4.

In Figure 4.4, the first two entities in the square bracket are source and destination address. The third entity is the type of the frame. I is the information frame. The fourth and fifth entities are $N(S)$ and $N(R)$. The acknowledgement of the received frame can be piggybacked with the transmitted frame sequence number.

Also, when the transmission error occurred during the transmission, no acknowledgement will be sent. The error will be detected if no acknowledgement is received for the transmission for a period. The error control mechanisms in the wireless network will be described in the following sub-sections.

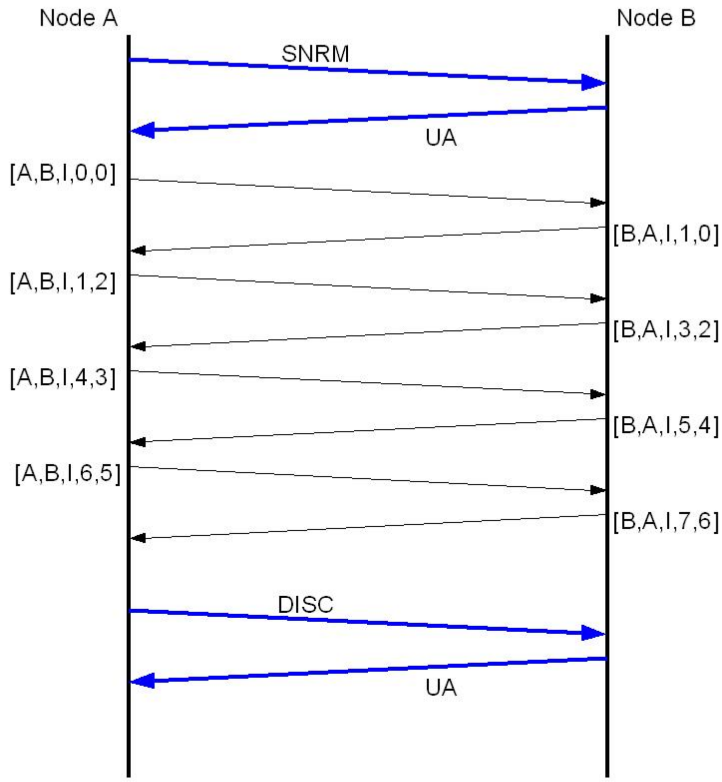


Figure 4.4 Normal response mode

4.3.1.2 Forward error correction

Error control is important to guarantee the correctness of signal transmission. Usually in a communication channel, two error control methods will be used in order to improve the reliability of transmission: Forward Error Correction (FEC) and feedback error correction (ARQ). The FEC is, by using redundant information attached in the transmitted frame, the transmission error can be detected and corrected. However, the FEC can’t guarantee the correctness of transmissions.

In the wireless network environment discussed here, the FEC is automatically provided by the CRC field in pre-programmed Modbus protocol. No further FEC is made in the protocol described in section 4.3.1. However, the FEC provided by the firmware will only drop the received frame once error is detected. No negative acknowledgement will be sent in the network channel. Therefore, a feedback error correction is also offered in this network.

4.3.1.3 Feedback error correction

The feedback error correction in data link layer is called ARQ. As described in chapter 2, it is a mechanism to improve the correctness of transmissions. For the ARQ protocols, there are three frequently used types: stop-and-wait ARQ, go-back-n ARQ, and selective reject ARQ. For the latter two ARQ methods, the transmission efficiency comparing to stop-and-wait ARQ are better. However, the cost is their relatively expensive computational needs since more buffers and data rearrangements are required. So the stop-and-wait ARQ is selected for the dedicated network here. The ARQ methods are shown found in Figure 4.5.

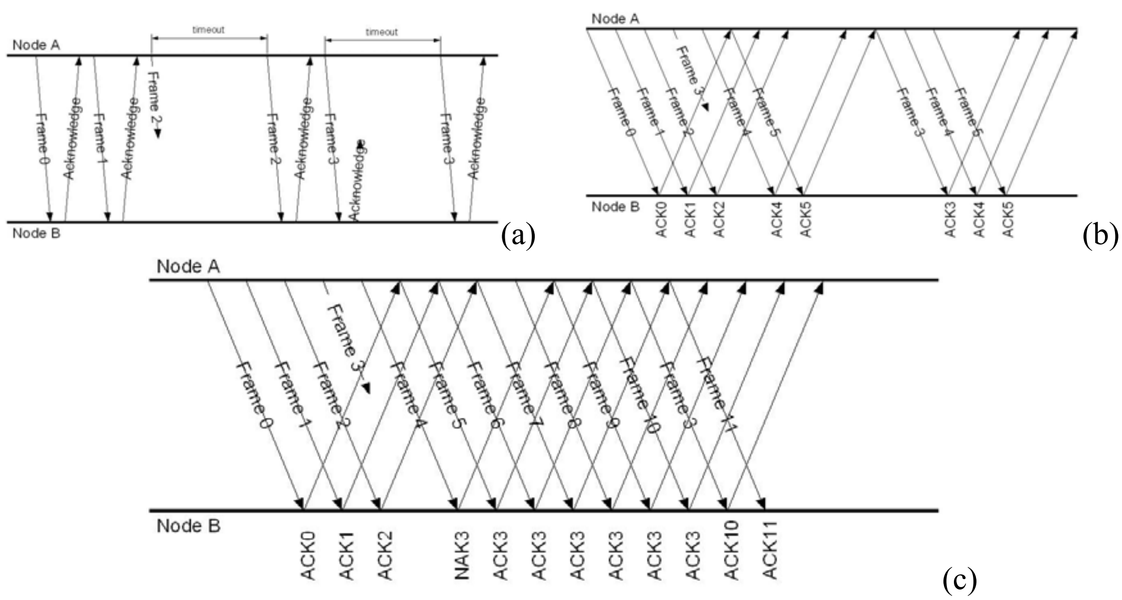


Figure 4.5 ARQ methods. (a) stop-and-wait ARQ, (b) go-back-n ARQ, and (c) selective reject ARQ

4.3.2 Agent Communication Language

Another appeared problem after two agents could have communicated with each other: How could the agent interpret the binary data into meaningful context? A common language for two homogenous/ heterogeneous agents is required in order to translate low level data into useful high level information or control command for different agents. The syntactic and semantic definitions for such a language hence have to be regulated. This task is defined in the presentation layer and application layer in ISO model. On the other hand, since the dedicated network environment has skipped over some intermediate layers, the compensation for some of these functions could have been made in the application layer. The Agent Communication Language (ACL) has therefore become another critical protocol for the multi-agent environments.

A few of the agent communication languages have been developed to satisfy the interoperability need between agents. It includes both semantic and syntactic definitions for the language. Two major ACLs have been developed and widely discussed: Knowledge Query and Manipulation Language (KQML) [33]~[34] and FIPA-ACL [35]. Usually the ACLs are comprised of different performatives with various lengths of the arguments and contents, depends on their requested actions. The information contained in each ACL is often encoded in the ASCII format, while the binary message encoding method is also used once in a while. However, the introduction of the ACL is quite lengthy and beyond the scope of this thesis. Therefore, a detail introduction for the developments and principles of ACL will be skipped over. The proposals and specifications for various ACLs could be found in [33] ~ [35]. This section will only focus the attention on the dedicated ACL proposal.

The ACL proposed here is composed of a couple of different components. Table 4.1 lists the essential components as the syntax of the language used in this thesis. Comparing to the other generic ACLs, this ACL proposal is restricted to a specific use for some fundamental operations for the multi-robot testbed mentioned in the previous chapter. For example: the query for the IR sensor reading, sending a command to request a motion on another robot, or monitoring the eligibility of a robot in the network. The detail semantics of the language are explained below:

Table 4.1 Proposed agent communication language

arguments	Bits	value	semantics	meanings
length	8	0x01 ~ 0xFF	n/a	indicate the length of the ACL message
sender	8	0x01 ~ 0xFF	n/a	message sender ID
receiver	8	0x01 ~ 0xFF	n/a	message receiver ID
performative	5	0x01	ask	ask for specific information
		0x02	tell	send the requested information
		0x09	unregister	inform the other agent of leaving the network
ontology	3	0x01	eligibility	value for eligibility
		0x02	motor speed	value for motor speed
		0x03	IR reading	value for proximity detection
		0x04	signal strength	values indicate wireless signal strength
		0x05	power	measurement for the remaining power
		0x06	camera	signal to turn on/off the embedded camera
		0x07	connection	information about the connection
service-request	2	0x02	data out	the information flow of the message
		0x03	data in	
in-reply-to	3	0x00 ~ 0x07	n/a	ID of a specific process for the message response regarding to
reply with	3	0x00 ~ 0x07	n/a	message ID regarding to the message itself

- *Length*

The total length of each ACL message is not fixed. So this field indicates the total length of the transmitted ACL message in order for the receiver to receive the message correctly. This is an 8 bits field.

- *Sender*

This field specifies the source of the information. Comparing to the source address in the data link layer, this ID is more flexible. It could be determined by the physical address or another specific ID due to the change of the network topology. This identification could be either the source address in data link layer protocol or a logical address. The range of the address is from 0x01 ~ 0xFF.

- *Receiver*

This field is similar to the sender mentioned above. The value indicates to receiver of the information. The range is also from 0x01 ~ 0xFF.

- *Performative*

The performative assigns the type of communicative act [35]. This field is 5 bits long, so the value can vary from 0x00 ~ 0x1F. The values which have already been assigned could be found in Table 4.1. This field indicates all the control command and information exchange for the conversion.

- *Ontology*

This term is used in conjunction with performative as an auxiliary statement to express and interpret the message. Here this field is used to specify the type of the information either requested or sent.

- *Service-request*

This is used here to indicate the direction of the information flow as another auxiliary statement for some implicit performatives.

- *In-reply-to*

This field indicates the ID of a specific process for the message response regarding to.

- *Reply with*

This field assigns a specific number for the identification when any further process and response is being made.

According to the above explanation, when we want to acquire the eligibility value from robot 4 to robot 8, we can send an ACL message as shown in Figure 4.6(a). The response for such an information query is in Figure 4.6(b). In Figure 4.6(a), no content is included in the message. In the replied message, only one value is needed for the eligibility query.

:sender	8	:sender	4
:receiver	4	:receiver	8
-Performative	1	-Performative	2
:ontology	1	:ontology	1
:service-request	3	:service-request	2
:in-reply-to	0	:in-reply-to	3
:reply-with	3	:reply-with	7
:content	(a)	:content	0x7A (b)

Figure 4.6 Examples of ACL messages. (a) request for eligibility value, and (b) response for eligibility query.

According to the explanation of the physical meaning for each field and the example, most of the messages transmitted by using the ACL are expected to be short. The overhead of each message then would occupy a lot of portion for the whole message length. This fact would reduce the performance of sending useful measurements across the robots. In order to improve the efficiency, instead of sending the ASCII coded message, the message in the ACL used here is encoded in a bit-wise manner. The structure of the ACL message could be found in Figure 4.2.

A significant advantage could be made for the bit-wise encoding method. As of the example found in Figure 4.7, the robot of 16 sends a message to the robot of 8 a command of moving forward with the speed 100 on both wheels. The ASCII encoded message is 129 bytes long. The time spent to transmit this message for a 38400 bps wireless modem is 0.0268 sec. However, the same message encoded in a bit-wise method is only 7 bytes long. The time required for transmission is only 0.00146sec. So the bit-wise encoding is only 5% long comparing to the ASCII encoding. The similar results could also be found in some relevant efforts under both KQML [36] and FIPA-ACL [37].

:sender	**16**
:receiver	**8**
-Performative	**TELL**
:ontology	**motor speed**
:service-request	**Data out**
:in-reply-to	**1**
:reply-with	**0**
:content	**L100 R100**

(a)

0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	1	0	0	1	0
1	0	0	1	0	0	0	0
0	1	1	0	0	1	0	0
0	1	1	0	0	1	0	0

(b)

Figure 4.7 Comparison between different encoding methods for ACL. (a) ASCII encoding, and (b) bit-wise encoding.

Figure 4.8 shows the performance comparison between the ASCII encoding and bit-wise encoding. It could be observed that the performance has significant improvements for the shorter message since the overhead for a shorter message is a heavy burden comparing to the longer message. Nevertheless, the efficiency for longer message will still be better comparing to the ASCII encoding method.

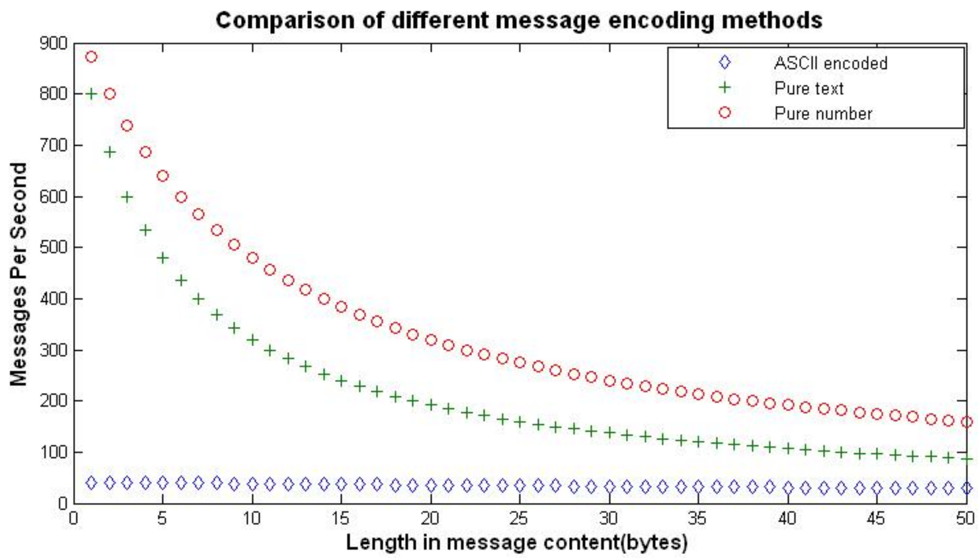


Figure 4.8 Comparison of the performance on different message encoding methods

This chapter provides a network environment for the communication needs between each robot. However, a mobile robot always changes it physical locations and sometimes needs to change the network topology corresponding to different incidents or mission requirements. Chapter 5 will proposed a procedure for the MRS testbed to configure their logical connections dynamically in order to gain the flexibility during the system operation.

CHAPTER 5
SELF-CONFIGURABLE TOPOLOGY

As in the centralized control scenario, all of the controlled devices connected to a single command center. The network topology is fixed and therefore less flexible. Any change of the connection or topology must be made from the leader in the network. However, for each single robot, the lack of the ability to configure itself in response to any event occurred regarding to itself reduces the autonomy on such a robot. As an agent in multi-agent system, the agent generally should have the following properties: autonomy, flexibility, and to own the thread to control itself. Therefore, the ability to be autonomous to the environment including network connections promotes a robot to an intelligent agent. a self-configurable network topology can also utilize the resources more efficiently and response to any incident faster. Moreover, the failures on the members of the MRS will not obsolete the operation of the whole system. Hence the system could also be more robust. Each member in the system is also easier to be replaced and upgraded. In the section 5.1, the use of an evaluation measurement is proposed to indicate the eligibility of each robot. The eligibility value could be determined by various mission objectives and multiple measurements on each single agent. Eligibility List (EL) can then be generated and broadcasted globally based on the collection of eligibility value on each available robot. Therefore, a dynamic task allocation method could be developed based on the awareness of eligibility on each robot. The related discussion about the dynamic task allocation can be found in [9] and [17]. Section 5.2 explains the procedure of the self-configuration using the EL. Two different operational modes are suggested to indicate the robot status as either leader or follower. The physical operations are demonstrated under various scenarios in the rest sections as the examples of the self-configuration procedure.

5.1 Eligibility List

The topology for the network is determined by the eligibility of each agent. The MRS is designed for homogeneous/heterogeneous robots interoperation. For each different single robot, different capabilities and resources are assumed. For example, the remaining power, wireless signal strength, and the location of itself could all affect the eligibility to perform the allocated mission tasks. The modules and actuators embedded on each robot might vary as well. For instance, a robot with only IR sensors might need to be guided by another robot with a camera so it could become location awareness. Also, the robot with higher processing performance might take leadership of the whole robot team. Therefore, the election of the most eligible robot to be the leading agent in the network can optimize the system performance. During the operation of MRS, an EL is generated by broadcasting the query to each robot. The EL contains two rows. The first row contains the ranking of the eligibility for each robot, and the second row contains the eligibility value for each robot. After the EL is generated, the list will again be broadcasted to each of the robot. While the control of the network topology is still seized by the leading robot, the most eligible robot could be determined and configuration on the topology based on the available eligibility information could be made. The self-configuration mechanism could also justify the unpredictable fault when the leading robot fails and replaces it with the next eligible robot. This self-configurable mechanism is discussed in the next section.

5.2 Self-configuration

A self-configuration mechanism is a critical request to take the system communication to an autonomous level. The network functions by scanning the network frequently from the leading robot, and the sensing of a connection timeout by the follower robot. For each of the robot in the network, the capability to adjust itself individually can be added by such a mechanism. Therefore, the biggest difference for this network is the control of the network topology is decentralized. The flowchart of the self-configuration mechanism is shown in Figure 5.1.

As shown in Figure 5.1, the operation of robot communication can be separated into two different modes: passive mode and active mode. When the robot works under passive mode, it waits for the connection request from the other robots. During this operation mode, the robot works as a follower under the command of the leading robot which connects to it. However, when the connection request isn't received over a period of time, or the leading robot un-register from the network, a follower robot will assume the leading robot becomes invalid and eliminate its existence from the EL. Then for each follower robot, an inspection for the eligibility list to determine the most eligible robot will be performed. The most eligible robot (with the highest eligibility value) will take over the lead of the network and enter the active mode. During the active mode operation, the leading robot will constantly scan the network to find the other available robots at a given rate. Once a more eligible robot is found, the leading robot will relinquish its privilege to control the other robots, return to its passive mode and wait for the connection request from the most eligible robot.

The self-configurable network contains four different scenarios: network initialization and new robot joining, follower failure, leader failure, and control privilege transfer. The execution of the procedure will be explained in the later sections as the simulation results for the network self-configuration mechanism. Before the demonstrations of these procedures, the test configuration for this self-configurable network is explained in the next section first.

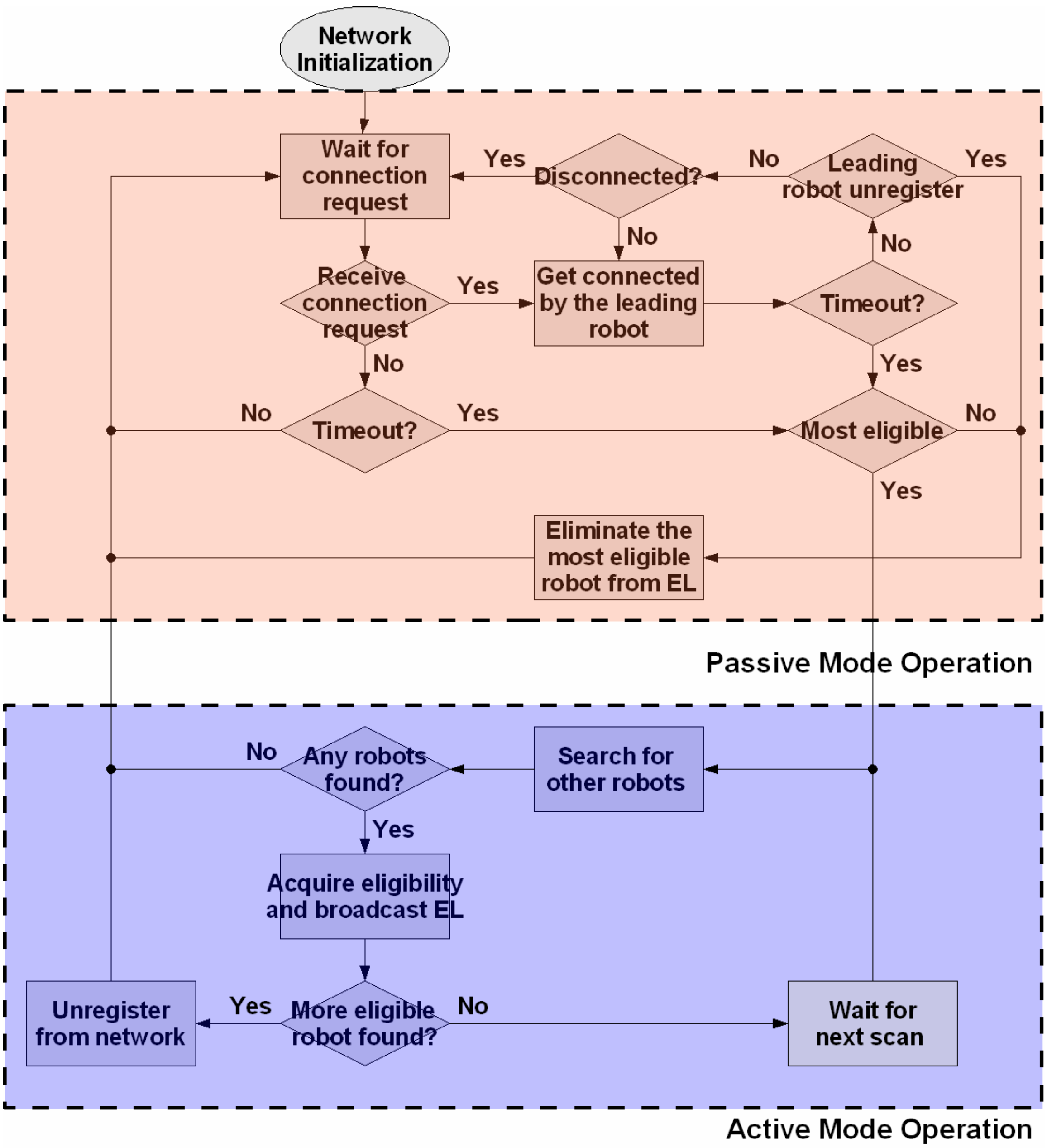


Figure 5.1 Flowchart of self-configuration mechanism.

5.3 Test Configuration

The WALKER is a prototype for wireless multi-robot testbed. With the proposed hardware architecture described in chapter 3, multiple WALKERs are capable to work cooperative within the testbed. However, due to the research progress, only one WALKER is manufactured currently for the hardware assessment. Therefore, tests of the communication network in the following sections are performed by similar computer equipments. Detail test configuration including wireless modem setting, used operating system, and software development tool chains are described below.

Table 5.1 lists all computers used for the tests. The computer one is the PC/104 processing module embedded on WALKER. Other two computers are Intel PC and SUN workstation respectively. The purpose for using different computers in the tests is also to validate the compatibility of the communication network between heterogeneous robots. However, all the tests are performed under Linux environments. The kernels used in all three computers are under the family of Linux kernel 2.4. (See Table 5.1) It is, nevertheless, not a real time kernel. The display during the execution is shown in Figure 5.2. In Figure 5.2, the program shows the value -1 to present the empty fields in the eligibility list.

Table 5.1 Computer configurations for the test.

	Computer 1	Computer 2	Computer 3
Processor	INTEL Pentium 266 MHz (PC/104 board)	INTEL Pentium 4 1.8GHz	SUN UltraSPARC-IIi 440 MHz
Memory	64MB	128MB	640MB
Operating System	White Dwarf Linux 2.0	Debian 3.0r4	Debian3.0r4
Linux Kernel	2.4.29	2.4.27	2.4.27
Hard Drive/ FLASH Volume	512MB	10GB	9.4GB
Compiler Version	Gcc 3.2	Gcc 3.3.5	Gcc 3.3.5

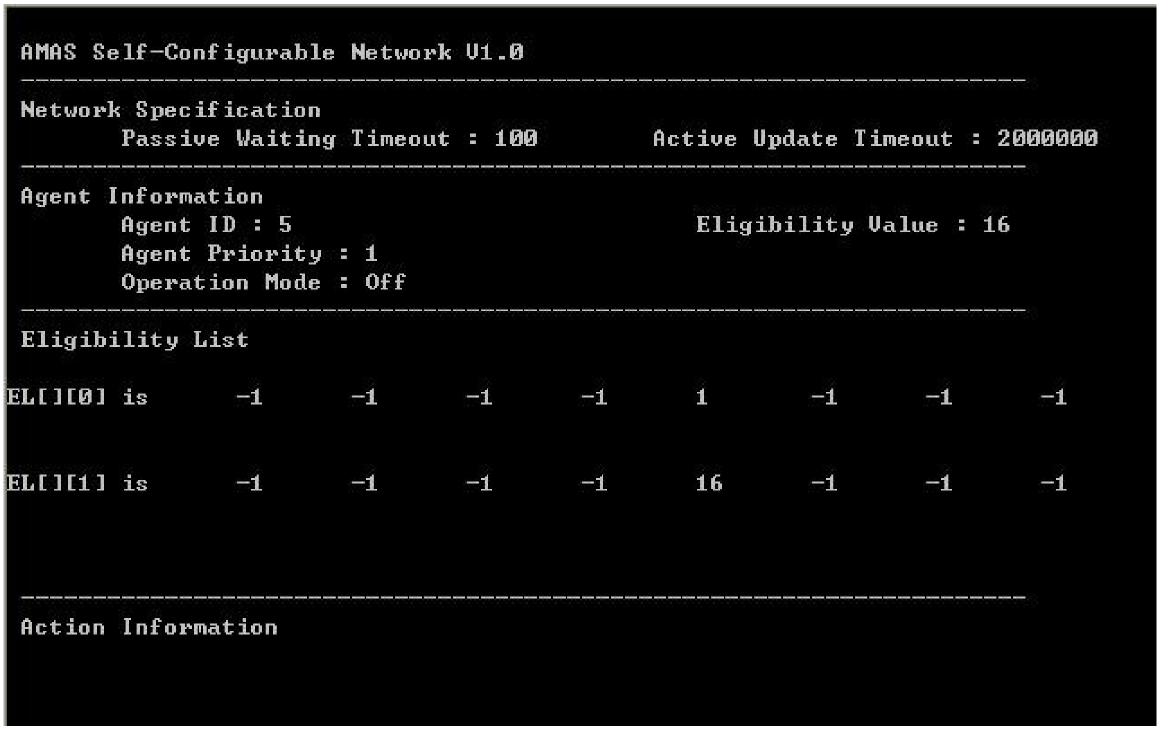


Figure 5.2 Display during the test.

5.4 Network Initialization

The network initialization process is shown in Figure 5.3. In the beginning both robots are in the passive mode. However, when the first robot gets the timeout from waiting, it will enter the active mode and scan the network for other available robots. The eligibility value will then be queried and transmitted between all the existing robots. The leading robot is responsible for ranking all the robots in the list and then broadcast the list to the robots which connects to it. The connection will be closed after the negotiation is complete in the last step and waiting for another scanning after a short period of time.

Also, the same process will also work when more robots attempt to join the network. The difference is when the leading robot scans over the network, more available robots will be found. The connections from the leading robot to all available robots will therefore be established and closed after it is finished.

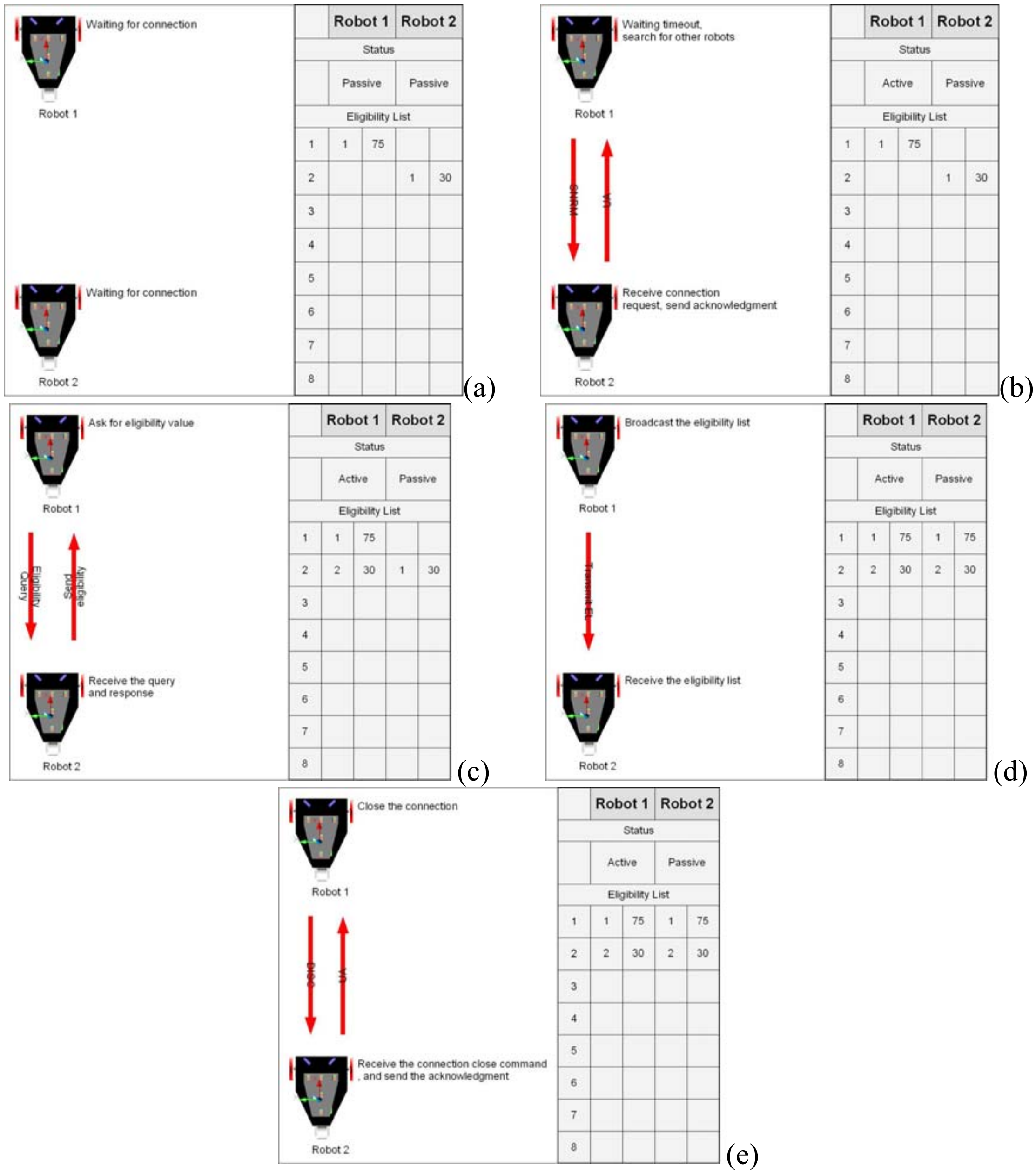


Figure 5.3 Network initialization process. (a)waiting for timeout, (b)connection established, (c)eligibility query, (d)EL broadcast, and (e)close connection.

5.5 Follower Failure

Another possible scenario is the failure of the follower. This incident can be detected and updated from the scanning by the leading robot. Once any available robot becomes invalid, the response for connection request will no longer be seen. So the failed robot will be removed from the EL at the leading robot. The new eligibility list will be broadcasted through the network. This procedure could be seen in Figure 5.4.

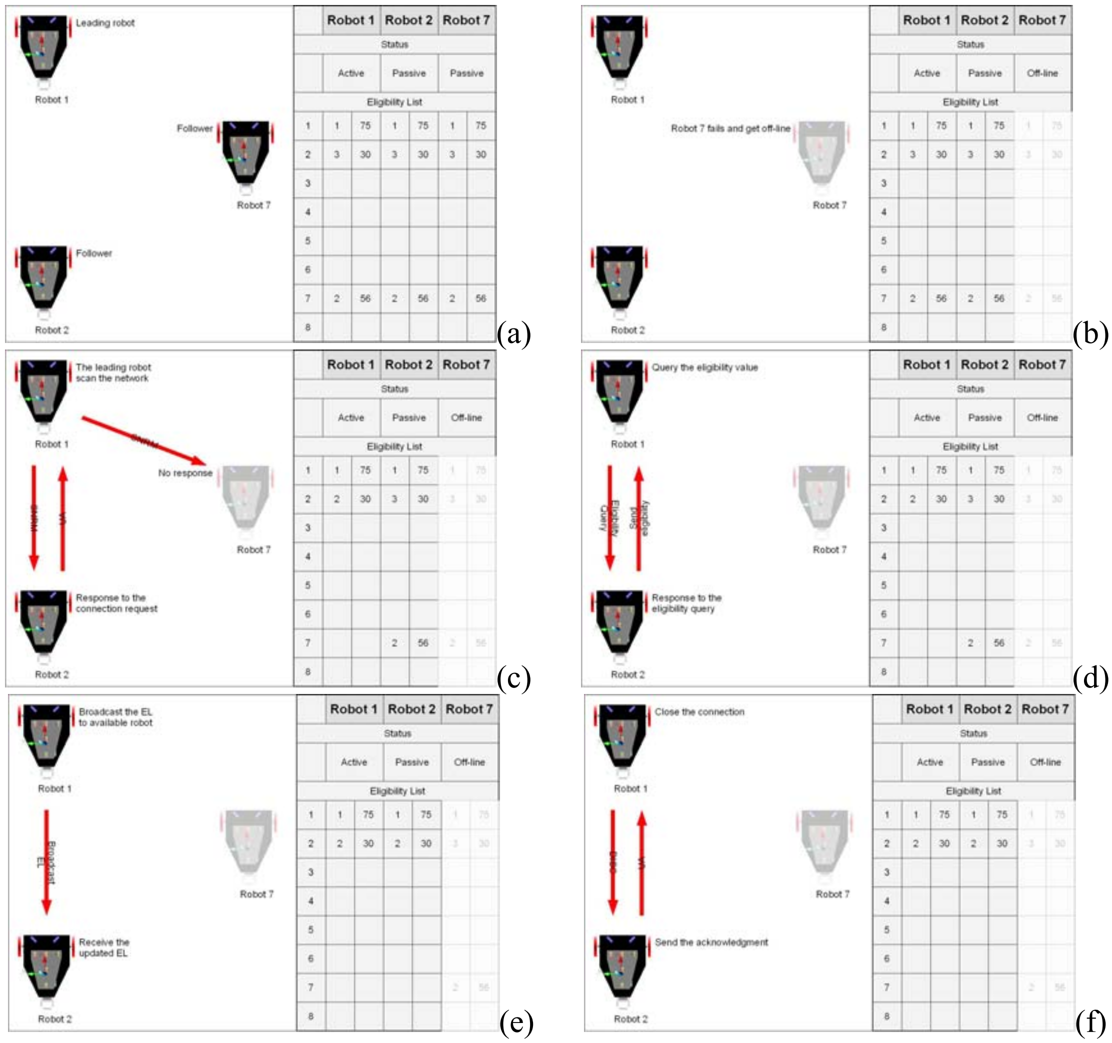


Figure 5.4 Topology configuration when follower fails. (a) a network with 3 robots, (b) robot 7 fails, (c) leader scans the network, (d) failed robot detected and removed from the EL, (e) broadcast the EL, and (f) finish the configuration.

5.6 Leader Failure

One of the requirements for the dedicated network is to be robust to the possible robot failures. A decentralized system could encounter the exceptional failure on any of its member. Therefore, for the system autonomy, the communication network must be able to accommodate itself to such an event, not only for the failures on followers but also the leader. The occurrence of the incident on any individual robot must not make the system operation obsolete. Therefore we need to consider a leader failure as well. The procedure to configure the network from the leader failure is shown in Figure 5.5.

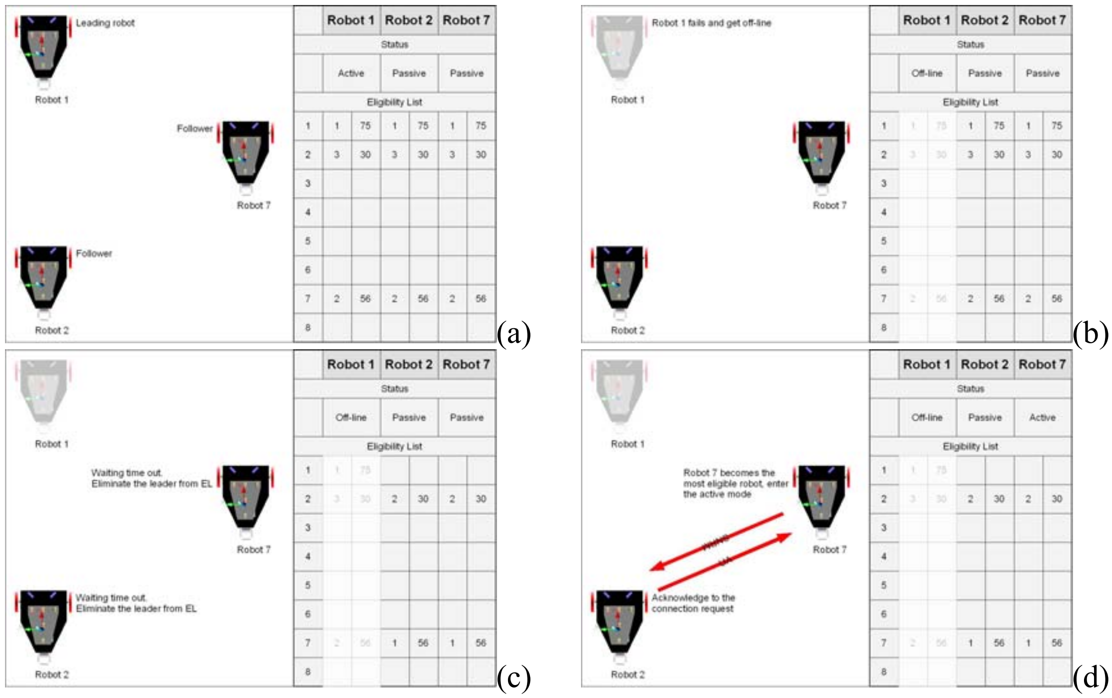


Figure 5.5 Topology configuration when the leader fails. (a) a network with 3 robots, (b) the leading robot fails, (c) time out form the connection waiting, and (d) network reinitialized by the most eligible available robot.

In Figure 5.5, when the following robots get time out from the connection request waiting, they will assume the leading robot failure occurs. The leading robot will be removed from the eligibility list on each follower. The next eligible robot among the rest will then become the most eligible robot, enter the active mode operation, and seize the control of the network, as shown in Figure 5.5(c). The network initialization will therefore be processed by the most eligible robot as explained in section 5.4.

5.7 Control Privilege Transfer

Another scenario that can occur in this network is the joining of a robot which has a higher eligibility value for the mission objective. A transfer of the leadership needs to be made in the network to a more eligible robot when found. The configuration is shown in Figure 5.6.

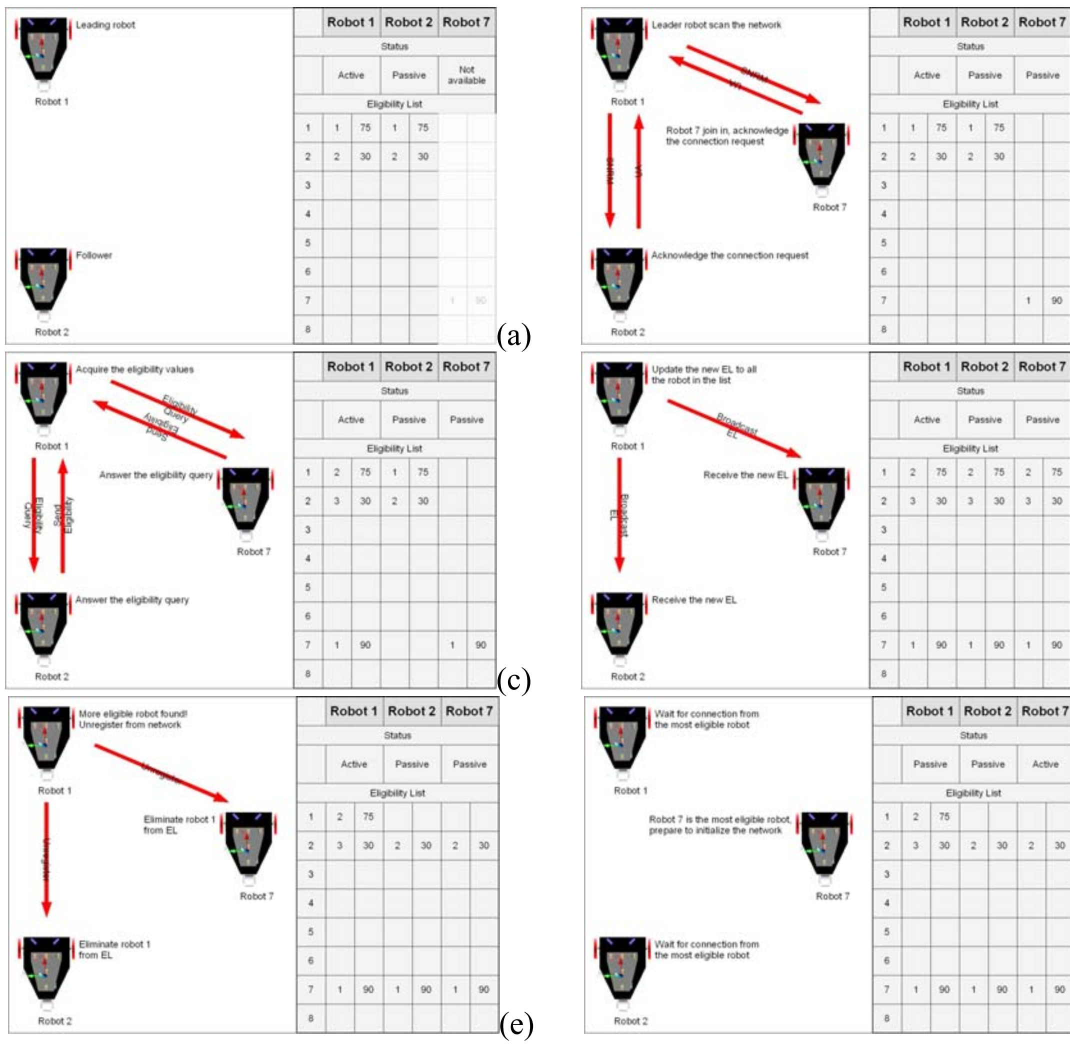


Figure 5.6 Topology configuration for the control privilege transfer. (a) a network with two working robots, (b) a more eligible robot attempts to join the network, (c) query for the eligibility value, (d) broadcast the EL, (e) leader unregisters from the network, and (f) a re-initialization is made by the new joining robot

When a more eligible robot is found by the leading robot, the leading robot will unregister itself from the network and be removed from the list. However, it will still stay in the network. As a result, the leading of the network will automatically be transfer to the higher eligible robot and take over the network control. When the higher eligible leader enter the active operation mode and scan the network, the original leader will then be found and join in the eligibility list again as a follower.

The self-configurable network discussed in chapter 4 and 5 is a semi ad hoc network. A hub to group and administrate the available robots is still a requisite in the network. However, a dynamic adjustment capability is added here regarding to the eligibility of each robot. This method is somewhat restrictive comparing to a MANET environment. However the network complexity is lower since the burden of using a network layer routing protocol is avoided. Therefore less hardware requirement is needed. It is especially a more efficient manner to implement a network in a MRS when the scalability has a lower priority.

CHAPTER 6
CONCLUSIONS AND FUTURE WORKS

This research presents the effort to establish the wireless multi-robot testbed for MAS research purposes. The revision from previous design shows significant improvements on both the capability and performance. A more autonomous multi-robot system with a more dynamic and flexible operation mode is created by using both hardware and software means in chapter 3 ~ 5. The work discussed in the thesis especially focused on a cost effective approach in terms of power and computational uses for the hardware implementation.

6.1 Conclusions

The applications for the MAS are widely developed and recognized recently result from the mature of critical technologies, such as theoretical developments, computer technologies, communication enhancements, and rapid growth of the embedded system industries. To recognize the pending physical systems as well as the theoretical issues and progresses is the initial phase before the design problem. It is presented in the first chapter.

Meanwhile, the network communications is an important prerequisite for the multi-robot testbed for any further theoretical validations on MAS. The interconnections must be made to organize homogeneous/heterogeneous robots into a fleet. A brief review on the rudimental knowledge of network communications is provided in this thesis as well as the reference for a network environment design problem.

The hardware design could be regarded as an embedded system design problem. Therefore, the discussions about the implementation emphasize the concepts of the design philosophies and how the signals and data flow over different modules in the testbed system. It is a valuable aspect for the testbed development so another similar design based on different requirements or further revisions could be made by referencing this implementation. In the experimental testbed a 32-bit Pentium processor is used on the robot in conjunction with sensors and necessary modules to perform an enhanced processing and sensing tasks for an MAS research needs. The approach used here is valuable for manufacturing a good cost-performance multi-robot testbed.

The lower layer wireless protocols extend the original protocols from peer-to-peer to network wide. However, the economic design has restrictions on the WAN and routing capabilities. The implementation of a more scalable network is beyond the scope of the thesis. Also, an initial version of ACL is proposed so the fundamental inter-cooperation between robots could be dealt.

The robot autonomy could be discussed in many different aspects from navigation, communication to health management and task allocation. This thesis also provides a self-configurable communication scheme for the more robust operation and system management. The mechanism is intuitive yet effective for the operation of the MRS. A more ad hoc environment could be developed based on a revision of the lower layer SDU overhead.

6.2 Future Works

The thesis presents a continuing work of developing a MAS research facility. It promotes the control scheme from centralized control in the previous job (see Kantor [12]) to a decentralized control scenario from the hardware and software aspects. However, there are still some significant restrictions for the system as mentioned eariler. For example, the positioning system still required wired signal transmission. Also, the ACL will need to be discussed further in order to support the operation in either a mission specific manner or a more general compatibility for robot inter-operations.

Also, for mobile ad hoc network, dynamic addressing will significantly improve the scalability of the network, further discussion can be found in [38].

The work discussed in this thesis only validates the implementation of the design. A further performance analysis is still needed to be discussed in the future. The hardware components could also be further optimized in both mechanical and electrical architectures as well.

APPENDIX
ACRONYMS

A

A/D	Analog to Digital
ABM	Asynchronous Balanced Mode
ACL	Agent Communication Language
ADC	Analog to Digital Converter
ARM	Asynchronous Response Mode
ARPANET	Advanced Research Projects Agency NETwork
ARQ	Automatic Repeat reQuest
ASCII	American Standard Code for Information Interchange

B

BPSK	Binary Phase Shift Keying

C

CCK	Complementary Code Keying
CDMA	Code Division Multiple Access
CRC	Cyclic Redundancy Check
CSMA-CD	Carrier Sense Multiple Access with Collision Detection
CSMA-CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear To Send

D

D/A	Digital to Analog
DARPA	Defense Advanced Research Project Agency
DART	Demonstration of Autonomous Rendezvous Technology
DNS	Domain Name Service
DTE	Data Terminal Equipment

E

EL	Eligibility List
EMI	Electro-Magnetic Interference

F

FCS	Future Combat Systems
FEC	Forward Error Correction
FIPA-ACL	Foundation for Intelligent Physical Agents - Agent Communication Language
FTP	File Transfer Protocol
FSK	Frequency Shift Keying

G

GPS	Global Positioning Systems

H

HDLC	High-level Data Link Control
HTTP	HyperText Transfer Protocol

I

IP	Internet Protocol
IR	InfRared sensor

ISO	International Organization for Standardization

J

JRP	Joint Robotics Program

K

KQML	Knowledge Query and Manipulation Language

L

LAN	Local Area Network
LED	Light Emitting Diode

M

MAC	Medium Access Control
MANET	Mobile Ad hoc NETwork
MAS	Multi-Agent Systems
MEMS	Micro Electro-Mechanical Systems
MODEM	Modulator/DEModulator
MP	Motion Planning
MRS	Multi-Robot Systems

N

NASA	National Aeronautics & Space Administration
NRM	Normal Response Mode

O

OSI	Open Systems Interconnection
OSD	Office of the Secretary of Defense

P

PC	Personal Computer
PDA	Personal Digital Assistant
PDU	Protocol Data Unit
POP	Post Office Protocol
PWM	Pulse Width Modulation

Q

QoS	Quality of Service
QPSK	Quadrative Phase-Shift Keying

R

RTP	Real Time Protocol
RTS	Request To Send
RWC	Robot Work Crew

S

SDU	Service Data Unit
SNR	Signal to Noise Ratio
SRAM	Static Random Access Memory

T

TDMA	Time Division Multiple Access
TCP	Transmission Control Protocol
TELNET	Telecommunications Network

U

UAV	Unmanned Air Vehicles
UDP	User Datagram Protocol
UMS	UnManned Systems
UGV	Unmanned Ground Vehicle

V

VPN	Virtual Private Network

W

WALKER	Wireless Autonomous Linux-based Kinematic Expert Robot
WAN	Wide Area Network

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BIOGRAPHICAL SKETCH

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