INTERNET-CONTROLLED ROBOTS AND WIRELESS SENSOR NETWORKS COMMUNICATION: PROBLEMS AND ISSUES.

by

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A THESIS

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Robotic systems have been widely utilized in factory automation, space exploration, military service and even in our daily life. Various control methods have been traditionally used for the robotic systems such as radio, microwave, computer networks etc. These control methodologies are the methods of teleoperation of robotic system. Internet is a dominating medium of communication. The robotic systems have turned to the Internet for remote accessibility. Internet-based teleoperation of robotic systems is coming of age. The sensors are increasingly striving to operate in the wireless ad-hoc network performing myriad functions and presenting umpteen utilities. Providing Internet connectivity to such sensor networks would make them truly ubiquitous.

The presented work identifies the problems and issues related to the Internet-based robotic teleoperation and the sensor networks. Current efforts in Internet-based robotic teleoperation carried out by individual groups lead to scores of specific solutions instead of a general framework. This work motivates the need for a general framework, which would bring about an overall solution and also address the Internet-related issues. Also the framework attempts to facilitate Internet connectivity to each of the architectures thus making an endeavor to uphold the paradigm of ubiquitous computing.
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DEDICATION

To my parents, Aai and Pappa

my brother, Rajendra and sister, Geetanjali
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<td>AODV</td>
<td>Ad-hoc On-Demand Distance Vector</td>
</tr>
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<td>CSMA</td>
<td>Carrier Sense Multiple Access</td>
</tr>
<tr>
<td>CTS</td>
<td>Clear to send</td>
</tr>
<tr>
<td>DSDV</td>
<td>Direct Sequence Distance Vector</td>
</tr>
<tr>
<td>HTTP</td>
<td>Hyper Text Markup Language</td>
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<td>MAC</td>
<td>Medium Access Control</td>
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<td>MANET</td>
<td>Mobile Ad-hoc Network</td>
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<tr>
<td>MEMS</td>
<td>Micro-electro mechanical system</td>
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<td>FCC</td>
<td>Federal Communications Commission</td>
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<td>OLSR</td>
<td>Optimized Link State Routing</td>
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<td>QOS</td>
<td>Quality of Service</td>
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<td>RTS</td>
<td>Request to send</td>
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<td>TCP</td>
<td>Transmission Control Protocol</td>
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<td>UDP</td>
<td>User Datagram Protocol</td>
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<tr>
<td>VRML</td>
<td>Virtual Reality Modeling Language</td>
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<td>WEP</td>
<td>Wired Equivalent Policy</td>
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<td>ZRP</td>
<td>Zone Routing Protocol</td>
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CHAPTER 1

INTRODUCTION

An area of robotics termed robotic teleoperation has been traditionally used to remotely explore undersea, deep space, to defuse bombs, clean up hazardous waste, factory automation and to some extent in our daily life. These systems have used the remote control methods like radio and microwave. The Internet has revolutionized the way in which we receive information and interact with the world. There has been an enormous increase in the number of devices accessible from the Internet. Some types of remote access technologies on the Internet such as the FTP, Telnet, WWW, email etc have provided convenient tools and devices to transmit remote information. The Internet is thus well poised to be a major communication medium for facilitating teleoperation.

At the same time, Internet-based robotic teleoperation brings along Internet specific issues like uncertain time delay problem, the latency, the uncertain data loss problem, and data transmission security problem. The robotic systems are classified into two types of networks namely the fixed infrastructure and the ad-hoc network. The security, communication and protocol issues for the two types of networks are diverse. There have been myriad implementations by individual groups, which have concentrated on specific solutions to reduce particular barriers to deploying the robotic system but leaving the other barriers intact. Many of the solutions used currently only partially solve the deployment problems. The solution works well for the case for which it was designed. This lack of common approach leads to varied efforts, which provide partially
superfluous solutions. These superfluous efforts arise from a variety of reasons, one of which is simply a lack of communication and publication. Many efforts have been detailed on the World Wide Web and nowhere else. The software and documentation resources available to those who intend to deploy the robotic system is limited. In addition to lack of familiarity with on-going projects, there is an additional problem in determining which efforts most closely match your own. Anyone who attempts to deploy the system has difficulty in overcoming the problem since information necessary to solve them is often spread across many web sites and is frequently missing the essential details.

The present work identifies the problems and issues relating to the Internet-based teleoperation of robotic systems. There is a dire need for a general framework, which would incorporate architecture with aim of reducing the barriers to deployment. The security, protocol, and the communication issues are taken care of in the architectures. The goal is extend the range at which robotic systems can be manipulated for deployment with an Internet connection. The goal leads to an extensible and generalized architecture for telerobotic operation. Also in recent times, haptics, the generic term for force sensing and perception by human, has gained considerable focus. Haptics can add the sense of touch and make an experience real to the user. Moreover, force feedback makes the action seem more real. Combining, Internet, robotics and haptics provide the essential tools to potentially build true teleoperation systems whereby users can not only see and hear but also feel and interact with remote objects.

Ad-hoc networks are evolving as a prime example of coming convergence of computing and communication. An architecture for robots in the ad-hoc network is also envisioned which would emphasize on the protocol, communication and security issues
which are apparently different from the fixed infrastructure ones. Robots in the ad-hoc networks have the potential to provide wireless and mobile computing capabilities in situations where efficient and rapid deployment of communication is required and where the use of an infrastructure-based wireless network is either too expensive or impractical. Such ad-hoc robotic networks bring about wide applications in emergency situations like disaster management, search and rescue operation, in military operations in the form of battlefield deployment of robots in combat and in cave exploring and mine searching. Thus such robots are envisioned to be deployed on reconnaissance duty in war-torn cities.

“Swarm Intelligence”, a collective behaviorism is being researched enormously for a wide range of applications. The potential of swarm intelligence is tremendous. Teamwork of ants have inspired scientists to program robots without the use of complex software. The cooperative interaction of ants has led to the development of more effective algorithms for robots. Mimicking an ant colony's way in dealing with its dead and sorting of their larvae has aided in analyzing banking data. In streaming assembly lines in factories, help has come from the division of labor among honeybees. The possibility of swarm intelligence being applied to ad-hoc robotic networks is being explored [1].

Wireless networks are arrangements of devices in which they communicate to each other via the wireless domain. Wireless sensor networks are an emerging technology. These networks find extensive potential applications, which include environment monitoring, in medicine in the form of health monitoring and remote sensing explorations. Such networks typically consist of a large number of distributed sensor nodes that organize themselves into a multi-hop ad-hoc network. The recent advances in computing technology have led to the creation of a new class of computing
device: Tiny low-power wireless battery powered- smart sensors. Researchers have
developed small sensor devices called Motes [2] and an operating system called TinyOS [3] that is suited to run on them. Motes are equipped with a radio, a processor and a suite of sensors. TinyOS makes it possible to deploy ad-hoc networks of sensors that can locate each other and route data without any a priori knowledge of network topology. Providing Internet connectivity to such sensor devices would make them truly ubiquitous. An architecture with the ultimate goal of furnishing Internet connectivity to these sensors is presented which would incorporate the protocols pertinent to achieving a reliable and efficient Internet connection.

1.1 Motivation

Through Internet-based teleoperation systems, human lives can be protected or saved because it eliminates the need of human to be present in hazardous environments like minefields and nuclear factory. Also, resources can be shared between users around the world. As such many users can share expensive and hard-to-find robots. The use of the Internet has also become very popular worldwide and thus, it is an inexpensive two-way communication link that spans across oceans and around the world. The Internet will surely get better. As the delays decrease and bandwidths increase, Internet-based robots will become very much like conventional teleoperation system. Then the characteristic of the Internet robots will be decided by the projected users and applications. The sensors are another entity, which need close attention. The sensor networks can cooperatively work in vital applications like habitat, crop and health monitoring. In particular health monitoring is an application where sensor networks can certainly help improve the
quality of life of the patients. The sensor networks thus would support the concept of “proactive health” [5].
CHAPTER 2

BACKGROUND AND RELATED WORK

Internet-based robotics has thrown open an entirely new gamut of real-world applications, namely tele-manufacturing, tele-training, tele-surgery, museum guide, traffic control, space exploration, disaster rescue, house cleaning, and health care. An Internet-based telerobotic system usually consists of a number of physical devices such as robots, cameras, sensors, and other actuators.

Although the Internet offers a cheap and readily available communication channel for teleoperation, there are still many problems that need to be solved before successful real-world applications can be realized. These problems include its restricted bandwidth and arbitrarily large transmission delay, which influence the performance of the Internet-based telerobotic systems. Some of the implementations advocate removal of human operators from the feedback control loop, and equip the robots with a high degree of local intelligence in order for them to autonomously handle the uncertainty in the real world and also the arbitrary network delay. Also an intuitive user interface is required for inexperienced people to control the robot remotely. The reliability of the system should be guaranteed so that Internet users can access the Internet robotic system 24 hours a day with minimum human maintenance. To cope with the low bandwidth and high latency imposed on Internet-controlled robots there is a need to make trade-off when sending information across the Internet robotic system.
Internet-based robotic teleoperation involves controlling robots from a web browser remotely and varies from traditional robotic teleoperation in several aspects:

1. The delay and the throughput of the Internet are highly unpredictable, unlike traditional teleoperation (for example space-based and underwater) where the interfaces have fixed and guaranteed delays.
2. Web-based teleoperation requires a high degree of tolerance to possible data-package loss due to packet discard when there is no existing remedy.
3. Internet robots need innovative mechanisms for coping with shared control among multiple web users with different applications in mind.
4. Internet robots are remotely operated by many people with little expertise and few skills. In contrast, traditional tele-robots are handled by trained operators.
5. Since web users are a central part of the control loop in Internet robots, their behavior becomes an important consideration in the system design [6].

2.1 Internet-based robotic teleoperation

![Diagram of Internet-based robotic teleoperation]

**Figure 2.1 Basic components of Internet-based robotic teleoperation**

To understand robotic teleoperation, the definition of robotics needs to be realized. Robotics is the science and art of designing and using robots. Robot can further defined as "a reprogrammable multi-functional manipulator designed to move materials,
parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks”. Furthermore, any electromechanical systems, such as a toy train, may be classified as a robot because it manipulates itself in an environment.

Teleoperation is the direct and continuous human control of a teleoperator. A teleoperator can be any machine that extends a person’s sensing and/or manipulating capability to a location remote from that person. In situations where it is impossible to be present at the remote location, a teleoperator can be used instead. These situations may be caused by the hostile environment at a minefield, or at the bottom of the ocean or simply at location that is impossible to travel. A teleoperator can replace human in any hazardous environments. Histories have shown that teleoperators have gone underwater to survey environment in the early 1970s, have translated through air and provided short range aerial surveillance in early 1980s and have been in minefield breaching operations in 1997.

Robotic systems operate in one of the two types of wireless network. One is the fixed infrastructure mode and the other is the ad-hoc wireless network mode. Robots in the fixed infrastructure have different types of control modes, which include the direct control mode, the supervisory control mode and the learning control mode. These robots in the fixed infrastructure mode specifically need an access point or a router to communicate within the system. Internet-based teleoperation falls into this category. Hence the Internet-based teleoperation is a fixed infrastructure mode operation where the robot server acts as the access point for the robot and other devices such as the camera, sensors etc.
Broadly speaking, Internet-based robotic teleoperation is typically the operation and control of a robot remotely using the Internet. The operator/user is furnished with tools to operate and control the remotely located robot. The tool is basically a Web-based Interface, which is running on a Web-browser on the user side. The basic components of the Internet-based robotic teleoperation are as shown in Figure 2.1. The Interface can be designed using utilities like the Java Applets, VRML tools etc. These tools are potentially user-friendly and provide a sleek interface for the user. The information to the web-interface is provided by the Web-server which hosts the information supplied by the robot and other devices like camera. The Web server also hosts a login service to ensure authority level for access to the robot. This facility is essential for the safety of the robot and its surrounding.

The robots can be broadly classified according to the Degree of Autonomy of the robot as follows.

1. Fully Autonomous robots. Robots, which require little or no control during operation. These robots carry local intelligence like collision avoidance, path planning, self-referencing, object recognition. Example: Sony Aibo, Robots used in supervisory control method.


3. Non-Autonomous Robots: These robots lack local intelligence and are thus called “Dumb robots” or “Slave robots”. Such robots require full control during operation. Example: Robots used in Tele-robotics that are operated in direct control method.
2.2 Control modes in Internet-based robotic teleoperation

1. Direct control: In direct control mode, the user has total control over the robot. The user provides low-level commands to control the robot. The robot executes the commands without any intelligence. In this mode, the robot behaves as a “puppet”. Due to the problem of Internet’s high latency and low bandwidth, direct control mode becomes problematic. To overcome this problem, researchers have devised the following approaches.

   a) Predictive aiding approach: This approach extrapolates forward environmental information and manipulator states in time by stochastic predictors for displaying on the user’s monitor.

   b) Simulation and Planning Display Approach: This approach uses local simulated manipulators to assist users to control the remote devices more intuitively. This user can control the simulated manipulator directly, and the computer stores the sample state-command pairs in the memory buffer. When the user has completed a task by a local simulated device, the queued data will be sent to the actual manipulator to execute.

   c) Wave transformation approach: This approach is based on the wave transformation. The control signal and sensory information transmission under an electrical line is considered the phenomena of wave propagation and energy scattering much more than as a pure data exchange. Based on this concept, the user orders the force command compensate the transmission delay time through force sensor feedback from the remote robot to ensure the remote system stability [7].
2. Supervisory Control: In this mode, the robot operates autonomously. Users need to only send high-level commands. The robot will execute the task using the built-in mechanism and local intelligence. This mode is essential to overcome the Internet latency problem and also for the safety of the robot. Using local intelligence the robot is capable of avoiding too many communication details from the Internet. Autonomy can help in reducing the bandwidth requirements for control, but this introduces problems of its own, particularly in the area of interactivity. People seem to prefer “hands on control” – in general, autonomous mobile robots do not provide the same type of immediate feedback, as do teleoperated robots.

3. Learning Control: There are two types of learning control modes depending on the longevity of the learned knowledge. These include:
   a) Long-term learning: This mode provides the operator with behavior programming control and also teaches the robot to complete a job so that the robot would repeatedly achieve the same job after learning. This mode is also useful to avoid the time delay problem.
   b) Short-term learning: This mode can be considered to be a new solution to the latency problem in the direct control mode. The basic concept is to allow the robot to be a more active device than a passive device in the direct control mode. The robot can learn human behavior from sensory information. Based on this knowledge the robot can autonomously handle tasks as learned before. The knowledge is updated on-line as the new command arrives hence this approach is termed short-term learning control.
2.2.1 Types of Control Architecture

Figure 2.2 Single robot control implementation [7]

The different types of control architecture available for the robotic systems includes the following.

1. One to One

Most systems provide one user control for one robot (one-one) as shown in Figure 2.2, such as in “KhepOnTheWeb” robot in which the system permits single remote user control the miniature mobile robot in the maze, and also provide real-time visual feedback to the user. Mercury, the first Internet-based system that allows users to remotely view and manipulate, is also the one-one control architecture.
2. One to Many

Some networked robot systems permit one user control for multiple robots (one-many). An example would be an automatic guided intelligent wheelchair system for hospital automation through the Internet. The control implementation is similar to the one shown in Figure 2.3.

3. Many-One

Few researchers propose that multiple users control a single robot system (many-one). An example would be a system, which allows multiple users to simultaneously teleoperate an industrial robot arm through the Internet.

4. Many to Many

Several researchers have devoted efforts to the multiple users-control-multiple-robots system (many-many). An example is the remote viewing system of an art museum in the KANSEI special project [7].
2.3 Classification of wireless networks

Wireless networks can be broadly classified into Data-centric networks and Communication-centric networks. The figure 2.4 clearly depicts the classification. The typical examples of data-centric networks are the Wireless LAN and the sensor network. In this type of network efficient routing of data takes preference. The examples of communication-centric network are the cellular networks, Ad-hoc Robotic networks and also MANETs. The realization of the sensor network applications need wireless ad-hoc networking techniques. The environment in which these sensor networks are deployed could be in remote geographical areas for the purpose of habitat monitoring. Hence it is self-evident that replenishment of power resources might be impossible or impractical. Hence such sensor networks could be deemed as limited in power resources. Hence the
sensor node lifetime shows strong dependence on battery lifetime. Hence in such networks power conservation and power management takes precedence over other factors. On the other hand in case of MANETs the power conservation is of secondary importance since replenishment of power is viable. Hence in MANETs and especially in Ad-hoc robotic networks, the primary focus is on provision of high quality of service (QOS) and also on bandwidth efficiency. This is apparent because the MANETs and the ad-hoc robotic networks are deemed as communication-centric networks. Moreover, the MAC protocols used in MANETs cannot be utilized directly for sensor networks. Thus the sensor networks would need energy optimized MAC protocol.

2.4 Mobile ad-hoc network

Mobile ad-hoc networks (MANET) are conspicuously different from cellular networks and WLANs. In MANETs there is no need for a central access point or base stations. These networks consist of mobile nodes engaging in peer-to-peer communication. The topology of this network is continuously changing and the nodes need to continuously update MAC level connection architecture and Network level routing tables. The pivotal goal for MANETs is to maintain routing abilities and network organization. Moreover MANETs are communication-centric networks while WLANs are data-centric networks.

The network priorities will dominate a trade-off for an increase in power efficiency and bandwidth optimization. MANETs support mobility. The network is designed for better throughput/delay characteristics in case of high node mobility. The
primary goal of MANETs is to maintain network connectivity and organization with secondary importance accorded to preservation of energy reserves.

2.5 Current Efforts in Internet-based robotic teleoperation

![System architecture of the Mercury project](image)

**Figure 2.5 System architecture of the Mercury project [8]**

1. The Mercury project

Goldberg and Mascha’s Mercury Project was an early effort at using the World Wide Web for telepresence research. The Mercury Project allowed web users to interactively excavate items with an HTML-based interface. The Mercury Project consisted of a UNIX server that handled HTTP requests, scripts and data serving. The rest of the system was composed of a PC-based robot server that manipulated the robot and camera and dealt with the results supplied by those devices. The two servers communicated via TCP/IP sockets. The web-documentation available for the Mercury project consists of Web-accessible conference papers that detail the design decisions and the functional breakdown of components. The security model implemented permitted a single person at a time to manipulate the robot after providing an appropriate password. In addition, the security model tried to prevent the damage to the robot by checking
commands for legality within the robot’s workspace. Latency issues were not directly addressed and the system used a move-and-wait model. Goldberg et al. attempted to achieve a high degree of reliability by limiting the amount of damage a user could cause through checking the legality of commands and checking for error codes. This architecture was reused for the Telegarden and the minimalist telerobotic installation. The current minimalist telerobotic installation architecture uses a device server to handle two-way communication with the devices and a CGI program running on a Web server to handle manipulated requests, access control and communication with the device server.

Figure 2.6 System in Kaplan car [9]

2. Kaplan car

Kaplan et al. built client server architecture to support the development of a remotely operated radio controlled car via the Internet. A goal of the project was to minimize the effort required to reuse standard software modules as much as possible. To a certain extent they succeeded in meeting this goal. They were able to replace the radio-controlled car with a radio-controlled airplane and presented plans for other possible uses. The Web-accessible documentation available for Kaplan car is minimal. A single paper was written and contains all the accessible documentation currently available. The
figure shows the architecture of the system. Video and audio feedback are possible through the use of Internet backbone (MBONE). They limit use and implement security through password-protected access. Latency was not addressed. Movement is carried out via the move-and-wait model by pulsing the motors and then reviewing the situation after movement has occurred. They used the same framework to also manipulate a radio-controlled airplane and intend to expand the project to include other devices in the future. Their solution provides for more immediate reusability than the Mercury project [9].

![Figure 2.7 Berkeley Blimp system [10]](image)

3. Berkeley Blimp

The Berkeley blimp is an attempt to provide a solution to floor-based movement limitations, as well as an attempt to provide a “body” for the remote user. Paulos and Canny have provided Web documentation, in the form of conference papers, on how the underlying client server system works, mentioning it is composed of HTML-embedded Java applets. Communication between the server and the blimp is carried out via radio. The client communicates with the server using standard Internet protocols. The server returns audio and video to the client via the MBONE. The high level architecture is similar to the architecture used by Kaplan et al. Latency issues are not discussed. The
Berkeley blimp has only minimal reliability. The Blimp’s security model allows one person to manipulate the Blimp while others can watch. The Berkeley Blimp is just one of the telepresence related projects undertaken by Paulos et al. under the auspices of their Personal Roving Presence (PROP) projects. The Berkeley Blimp’s architecture suffers from the same limitations as the Mercury project and the Kaplan car [10].

![Diagram of On-Board and Off-Board system in Xavier Project][1]

4. Xavier

One of the most successful deployed Web robots is Carnegie Mellon University (CMU’s) Xavier. It has been web-accessible since late 1995, permitting users across the world to navigate it around the building where it was stationed. Like several existing telerobotics efforts, its goals do not focus directly on telepresence. It was originally deployed as a way to test and demonstrate the efficacy of a new autonomous navigation algorithm. It differs from most Web-based telerobotics deployments in that the robot is

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autonomous. Instead of moving the robot down the hall or moving its arm, the user tells Xavier to move to a specified location such as an office. Xavier uses its autonomous navigation system to find the path to the given location. Xavier falls outside the typical model seen in most deployed architectures because the computers responsible for controlling the robot are on-board. Xavier receives its external commands and returns its feedback in the form of pictures via a wireless system. Web-accessible documentation is in the form of on-line copies of conference papers, which detail the underlying deployed system. Xavier breaks tasks into on-board and off-board categories. Navigation and half of the wireless communications are on-board tasks. A Web server, Web manager and task manager handle off-board activities. The task manager is responsible for scheduling requested tasks, while the Web Manager is responsible for refreshing the Web pages displayed by the Web server. Security is not addressed directly. Latency is not as large an issue with Xavier as it can be for other Web-based robots because of its high level commands. Reliability was achieved through trial and error by fixing problems as users uncovered them. Xavier relies on known map, a sophisticated autonomous navigation system, and a wireless infrastructure [11].
5. Puma Paint

The Puma Paint project is an online robot that allows World Wide Web users to produce original artwork. Users with Java compatible Web browser could control the PUMA robot. The project adopted an approach of time-delay teleoperation called “teleprogramming”. This approach was shown to reduce and potentially eliminate the delay introduced by “move and wait” strategy. Operators interact with a virtual representation of the remote site and from that interaction commands are sent across a distance and time barrier to the robot for execution. The completion time of the remote task was one round trip communication delay longer than the completion time if performed locally. The desynchronization between the operator’s commands and the robot actions is the characteristic that distinguishes a teleprogramming approach to remote control [12].
## Table 2.1 Summary of current efforts in Internet-based robotic teleoperation

<table>
<thead>
<tr>
<th></th>
<th>Mercury</th>
<th>Xavier</th>
<th>Berkeley Blimp</th>
<th>PumaPaint</th>
<th>Kaplan Car</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Telepresence</strong></td>
<td>✔️</td>
<td>✗</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td><strong>Direct Control</strong></td>
<td>✔️</td>
<td>✗</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td><strong>Supervisory Control</strong></td>
<td>✗</td>
<td>✔️</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td><strong>Teleprogramming</strong></td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✔️</td>
<td>✗</td>
</tr>
<tr>
<td><strong>Autonomous Robot</strong></td>
<td>✗</td>
<td>✔️</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td><strong>Slave Robot</strong></td>
<td>✔️</td>
<td>✗</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
</tbody>
</table>
Chapter 3

Thesis Work

Architecture is the backbone of robotics and sensor networks. The right kind of architecture helps in facilitating the specification, implementation and validation of these networks. A common feature found in these networks is their growing complexity.

Managing this growing complexity is the main goal of the presented architectures. Managing complexity demands architectures that delineate parameters of the system clearly and employ well-defined concepts.

The unified framework envisioned and conceptualized consist of three component architectures which include the following

1) Robotic teleoperation architecture.

2) Ad-hoc robotic network architecture.

3) Sensor network architecture.

The common goal of all these architectures is to address at a higher level the gains and the trade-offs that can be achieved using the different components of the individual architecture.
3.1 Unified Framework

The unified framework is the big picture envisioned, composing of the various architectures. The unifying component is the Internet. Three different architectures namely the Robotic teleoperation architecture, the ad-hoc robotic architecture and the Sensor network architecture are the composition of the unified framework. Each of the architecture is detailed accordingly.
The robotic teleoperation is considered to be a network-centric architecture where the data and communication are dependent on the underlying network used in the teleoperation system. The ad-hoc robotic architecture is typically a communication-centric architecture where communication between the robot nodes takes precedence. The sensor network is essentially a data-centric network where the efficient data transfer from the sensor node to the sink is of prime importance. For the sensor network the sink acts as the gateway between the sensor nodes and the Internet. In the ad-hoc robotic network, the ad-hoc bridge/router acts as the gateway between the ad-hoc robot nodes and the Internet. The unified framework paradigm has come into being due to the Internet. The primary goal of the unified framework is to extend the concept of ubiquitous computing to each of the architecture components. Hence, due to the accessibility of each of these components to the World Wide Web users, the concept of ubiquitous computing is upheld. As a result, there is an enormous increase in the number of Internet-accessible entities. Thus each of the architecture is envisioned keeping in mind the pivotal goal of ubiquitous computing.
3.2 Communication technologies available for robotic and sensor network

Table 3.1 Communication technologies available for robotic and sensor network

<table>
<thead>
<tr>
<th></th>
<th>Infrared</th>
<th>IEEE 802.11b</th>
<th>Bluetooth</th>
<th>UWB</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF band (GHz)</td>
<td>2.4/5</td>
<td>2.4/5</td>
<td>3.1/10.6</td>
<td></td>
</tr>
<tr>
<td>Modulation</td>
<td>DSSS</td>
<td>FHSS</td>
<td>PPM/TH</td>
<td></td>
</tr>
<tr>
<td>Data Rate (Mbps)</td>
<td>0.1-0.4</td>
<td>11 (shared)</td>
<td>0.72</td>
<td>56 Mbps</td>
</tr>
<tr>
<td>Range (m)</td>
<td>4</td>
<td>30-100</td>
<td>10-100</td>
<td>10</td>
</tr>
<tr>
<td>Network</td>
<td>PPP</td>
<td>Infrastructure and Ad-hoc</td>
<td>Ad-hoc</td>
<td>Short-range Network</td>
</tr>
<tr>
<td>Power</td>
<td>5mW</td>
<td>1W</td>
<td>0.3mW-30mW</td>
<td>0.5 mW/7 GHz</td>
</tr>
</tbody>
</table>

Infrared technology is being primitively applied in large scale in wireless robotic communication mainly due to its low cost. Study shows that there are drawbacks to this technology which include failure to pass through obstacles (e.g. wall), poor communication rate and quality. Radio frequency (RF) technology is found to be better for mobile robot communication. Robots are able to communicate in the system using RF point-to-point or broadcasting mechanism. The frequency hop spread spectrum (FHSS)
and direct sequence spread spectrum (DSSS) modulation technologies are being widely applied at the ISM (Industrial Scientific Medical) band (2.4GHz), which is license-free in several countries. The proliferation of Internet-based networks has given rise to application of Wireless LAN (IEEE 802.11, used in both infrastructure and ad-hoc network), Bluetooth standards for ad-hoc networks and ultra-wide band (UWB) radio.

In the robotic teleoperation architecture, the technology employed is the 802.11b. The reason being that in robotic teleoperation the wireless technology does not play an important role and a choice of high data rate wireless technology is sufficient. The wireless link is a facility to provide mobility to the robots operating in the robotic teleoperation architecture. Hence looking at the requirements and the economic aspect, the 802.11b standard is chosen as the underlying technology for the robotic teleoperation.

In the ad-hoc robotic network, the main concerns are bandwidth efficiency, high throughput and low delay. In other words the focus is on high QOS. For this purpose, the UWB is the most ideal wireless technology available. But currently, UWB only supports short-range networks due to the power level restrictions imposed by the FCC. Short-range level is totally unacceptable for ad-hoc robotic networks which may have to be remotely controlled for distances which far more exceed 10 meters. This is due to the fact that ad-hoc robotic networks are envisioned to be operated in alien environments and situations where the knowledge of the habitat in which the robots will operate is unknown. Hence there is an obligation to provide as much remote mobility for the robots by way of facilitating maximum wireless range possible. Hence, the current UWB implementation is not feasible. So the search for another technology which provides better range and the other requirements is the 802.11b standard. This standard has the
ability to provide multi-hop communication required by the ad-hoc robotic network. Also the bandwidth and throughput requirements are fairly good. Moreover using the 802.11 b standard, facilitation of Internet service to the network is convenient with the use of ad-hoc wireless bridge. Hence 802.11b is employed as the wireless technology for the ad-hoc robotic network.

In sensor networks, due to the power conservation aspect, the UWB would have been the ideal technology since UWB can efficiently operate in low power levels. But again the short-range factor of UWB comes to haunt. Sensor networks are put in service in remote environments for habitat and crop monitoring, which calls for long-range, network deployment. Hence it is infeasible again to use the current implementation of UWB in sensor networks. So the next available technology is the 802.11b standard. Due to the employment of 802.11b though, there would a dire need to implement an energy-optimized design of MAC protocol.
3.3 Internet-based robotic teleoperation

3.3.1 Internet-based robotic teleoperation architecture

![Architecture for Internet-based robotic teleoperation](image)

**Figure 3.2 Architecture for Internet-based robotic teleoperation**

Common architecture goals and implementations:

1) Provide a user-friendly web-based user interface in order to facilitate users with little expertise in operating and controlling remote robots. This is accomplished with the use of browser tools like VRML97, Java3D API at the users side. Also the web server could host applications like Java applet, which can be dynamically downloaded on the user’s browser application.

2) Robots: The robots employed here are considered to be ‘slave’ robots with no local intelligence. Hence the control mode operation is the direct control. This signifies that direct control allows the user/operator low-level control of the robot.
This brings to focus the need for architecture, which should be insensitive to Internet delays. Hence the Internet delay control architecture is employed.

3) Provide better transmission protocol for speedy data transfer over the Internet. Focus should be on on-time delivery rather than reliable delivery. This is because reliability causes unbearable delays. TCP is designed for reliable data communications, on low bandwidth, high error rate networks. UDP on the other hand is a connectionless datagram delivery service. UDP supplies minimized transmission delay by omitting the connection setup process, acknowledgement, and retransmission. UDP outperforms TCP in terms of delay and delay jitter. Thus from the point of timeliness and on-time delivery, UDP is more suitable for delay sensitive data transmission of the Internet-based robotic teleoperation.

4) Employ 802.11b standard for wireless link between the robot and the robot server. Here, the backbone communication topology supported by 802.11 standard is put in to service. This implies that the robot will communicate wirelessly via the access point, which is the robot server in this case.

5) Implementing security feature in order to ensure the safety of the robot from malicious users and hackers. This is accomplished by providing login service in the web server. This facility will help to set the authority level for access. The use of wireless medium opens another venue for initiating link level attacks like passive eavesdropping. Hence due to the use of 802.11b for wireless data transfer between the robot server and the robot, WEP encryption technique associated with 802.11 will need to be implemented for security from “wireless hackers”.

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Thus, Wired Equivalent Policy (WEP) is used in 802.11 networks to protect link-level data during wireless transmission from eavesdropping and other attacks.

3.3.2 The Internet time delay control architecture

![Diagram of Internet time delay control architecture]

**Figure 3.3 Internet time delay control architecture**

The Internet time delay control architecture is designed to minimize the effect of the Internet time delay. The Internet time delay control architecture consists of a user interface, simulator, virtual habitat and posture calculator. The robot simulator is like the virtual mobile robot, which is at the local side. Posture calculator estimates the current posture of the virtual robot based on the feedback information of the real robot. Posture calculator corrects the error between the real robot and the virtual robot. Virtual habitat has the information of the real habitat so that it enables the virtual robot to avoid obstacles. In order to correct the posture error between the virtual robot and the real robot, the real robot generates feedback signals such as posture information of the real robot, to the simulator [13].
1) Direct control robotic teleoperation: To cope with the Internet delay through the implementation of the Internet delay control architecture. This aspect has to be kept in mind due to the fact that in this particular scenario robotic system is directly controlled over the Internet and the robots used are lacking autonomy and local intelligence. In short the robots are assumed to “slave” robots. At the same time the robot is assumed to be possessing obstacle avoidance capability in order to prevent damages to the robot and also the surroundings. This capability is essential in the eventuality of overall system failure. In this case the user/operator has to supply low-level commands to control the robot. Such type of control is termed as the direct control robotic teleoperation.
2) Supervisory control robotic teleoperation: In the other scenario when an autonomous robot is used, the Internet transmission delay is not an issue because the robot through its local intelligence like collision avoidance, path planning, self-referencing, object recognition etc. has the ability to protect itself and its environment. In this case the user/operator has to furnish high-level commands to control the robot. Such type of control is termed the supervisory control robotic teleoperation.

3.3.3 Architecture accomplishment

The architecture accomplishments include the following.

1. Identified and defined all components necessary for the realization of Internet-based robotic teleoperation. These components include the robot server, image server, robot (both autonomous and slave robot), and Web server.

2. Presented the strategy for coping with the uncertain time delay problem posed by the Internet when direct control teleoperation is desired. This strategy is namely the Internet time delay control architecture.

3. Classified the robotic teleoperation system. This classification is essentially based on the fact that the robotic teleoperation is a closed loop system. Further this is sub-classified into direct control and supervisory control operation. The robots operating under the two different control schemed have also been pointed out. These include the slave robot in the case of direct control system and an autonomous robot in the case of supervisory control.
3.3.4 Summary

The underlying robotic teleoperation architecture component is using the Internet as the communication medium. The introduction of Internet brings along the uncertain time delay problems in the event of remote direct control of the robot. This gives rise to the architecture to cope with the time delay problem. Another way to suppress the problem of Internet time delay is the use of autonomous robot, which possesses local intelligence, path planning, and obstacle avoidance features.

The Internet-based teleoperation architecture composed of the following components:

1. Web Server: This component typically functioned to provide the Web user / operator with the information of the remote environment, which includes response from the remote robot and other devices such as images from the camera. The Web server also acts as the gateway for the command forwarding to the robot server. The Web server also hosts the security service by enabling a login service for the Web- users, which ensure authority-level access to the robot.

2. Robot Server: The robot server component hosts the robot command information and also acts as the storage system for the information obtained from the robot after the command is execute by the robot. The robot server typically queues the commands obtained from the Web server. Eventually, the robot server forwards these command information to the robot in a sequential manner.
3. Image Server: The image server, which resides in the communication sub-system along with the robot server at the remote site, performs the duty of hosting the image information obtained from the camera located to gather the images of the robot actions and responses. The image server also forwards the commands from the Web server, which is originally issued by the operator/user, which is located at the far end of the system.

4. Direct Control Robot: This robot is employed in the architecture where direct control of the robot for “hands on control” is desired by the remote operator. In order to fulfill this requirement, Internet control architecture is put in service in order to cope with the uncertain time delay problems introduced by the Internet. The robots in this type of teleoperation are considered to be “slave” robots. The operator is in total command of the robot. The user/operator issues low-level commands to the robot. Both One-to-One and Many-to-One control type of operation works in this architecture.

5. Autonomous Robot: Another smart way to tackle the Internet delay problem is to operate an autonomous robot. This robot virtually eliminates the time delay problem posed by the Internet.
3.4 Ad-hoc robotic network

3.4.1 Need for ad-hoc robotic network

A team of robots that is dispersed in a habitat to perform functions like monitoring or surveillance need to pass the information to a single point of collection. Such robots are mostly equipped with low power wireless transceivers whose range is too short to allow direct communication with the central collection point. Here it would be feasible to allow the robots communicate with its close neighbors. In this scenario, ad-hoc wireless networking comes in handy and becomes a good option. The disadvantages of centralized control for the team of robot are apparent in the sense that they could possibly lead to single point of failure. This indicates that centralized control and communication would easily lead to fatal system breakdown. Also in certain cases, centralized system is rendered a bad choice in terms of design and cost. On the other hand, decentralized and distributed systems involving team of robots supporting ad-hoc system properties are a feasible solution. They exhibit robustness to local failure and support scalability.

In unpredictable and unplanned environments mobile robots are called upon to create a wireless network to cooperate and schedule tasks. Here they are expected to be a multihop network capable of self-creating and self-organizing to meet the goals. In this manner decentralized approach applied in ad-hoc networks safeguards against single
point of failures. Internet is a glaring evidence of the power of the decentralized control and communication paradigm. Moreover, tasks may be inherently too complex (or impossible) for a single robot to accomplish and performance benefits can be gained from using multiple robots. Building and using several simple robots can be easier, cheaper, more flexible and more fault-tolerant than having a single powerful for each separate task [14].

3.4.2 Characteristic features of wireless ad-hoc network

An ad-hoc network is formed by a collection of network nodes with wireless communication capability. It does not rely on central entity or infrastructure (e.g. base station or access point) for communication. Two nodes can communicate directly if they are within radio range of each other. If out of range, the nodes can communicate through one or more intermediate nodes. In such a case, the intermediate nodes act as routers and relay packets from the source node to the destination node. Most ad-hoc networks include nodes that have limited resources typically limited battery life. Hence such networks can be termed resource-constrained networks. The topology of an ad-hoc network changes dynamically due to nodes changing their point of connectivity. The topology changes as nodes move out of range of one or more nodes with which they are connected and move closer and connect to other nodes. Thus in an ad-hoc network, the topology has to undergo frequent changes. In ad-hoc networks, nodes have to play multiple roles like being both the host (source or destination for data flow) and also as router. In other words, the nodes are expected to route packets for other nodes in the network while they themselves may be a source or destination for data flow. Thus the architecture must
account for the multiple roles played by the robot nodes. Thus the focus of the architecture should be efficient protocol employment in ad-hoc robot network.

### 3.4.3 Ad-hoc routing protocols

<table>
<thead>
<tr>
<th></th>
<th>DSDV</th>
<th>AODV</th>
<th>ZRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proactive</td>
<td>×</td>
<td>✔</td>
<td>Partly</td>
</tr>
<tr>
<td>Reactive</td>
<td>✔</td>
<td>×</td>
<td>Partly</td>
</tr>
<tr>
<td>Hybrid</td>
<td>×</td>
<td>×</td>
<td>✔</td>
</tr>
</tbody>
</table>

Routing algorithms can be classified based on their method of routing table maintenance, which is either Table-Driven or On-Demand. Proactive or Table Driven protocols are analogous to the connectionless approach to packet forwarding. All nodes in the network are made aware of all the routes leading to all other nodes in the network. Reactive or On-Demand routing techniques wait for a route to be requested before it will form, causing a node to delay packet transmission until the route has been established thus resulting in packet delay. On-Demand routing attempts to find the best path from source to destination immediately prior to message transmission. As a result, this method does not incur extensive signaling overhead associated with routing table formation but
imposes a delay on each message transmissions as paths are established. Reactive protocols are either source initiated or destination-initiated. Since Ad-hoc networks are assumed to be energy constrained, this delay is acceptable as the signaling overhead and power consumption is reduced due to routing information propagation.

Proactive or Table Driven routing protocols such as DSDV require each mobile node to maintain and update routing tables to all nodes within the network. In reactive protocols such as AODV and DSR, the source node initiates a path discovery process, by flooding a control message when a data message is sent. The recipient then replies to the sending node with the optimal path formation. AODV is thus termed a source-initiated reactive protocol. Proactive routing protocols can be deployed in a small size and slow topology-changed network. Reactive protocol may be more suitable for a large scale and fast topology-changed network. Latest protocols have indicated a combined use of both proactive and reactive methods. ZRP proposes that table driven methods can be used to route packets from zone to zone within the network with inter-zone routing carried on a demand-only basis. ZRP is conducive for large networks. The large network can be divided into small subnets. The proactive component of ZRP can be used in subnets while reactive component can be used among subnets [15].
3.4.4 Architecture design considerations

The following are the architecture design considerations.

1) Choice of a suitable protocol in the Transport Protocol layer, which is suited to work better in the ad-hoc robotic network. Research says that TCP does not perform well in ad-hoc networks. UDP (User Datagram Protocol) works better in ad-hoc networks. Hence UDP is employed in the underlying architecture. UDP is a simple transport protocol, which makes it faster than TCP since it imposes lesser overhead to each packet.

2) Choice of efficient ad-hoc routing protocol for routing packets between robots in the ad-hoc zone. This need calls for a protocol designed for mobile ad-hoc networks. There are several ad-hoc routing protocols, which are either proactive or reactive protocols. An example of proactive protocol is the Optimized Link State Routing Protocol (OLSR) and that of reactive protocol is Ad-Hoc On-Demand Distance Vector (AODV) protocol. A hybrid protocol namely Zone Routing Protocol (ZRP) is a protocol typically designed for mobile ad-hoc networks. It is a hybrid protocol that is part proactive and part reactive. The proactive part is called intrazone routing protocol and the reactive part is called the interzone routing protocol. Hence the ZRP is employed in the architecture for overall system gain.
3) The MAC protocol redesign with the high QOS requirements under consideration. The high QOS would signify the high throughput and low delay. This is an essential requirement because the architecture is being formulated for the ad-hoc robotic network, which is a communication-centric network. Though energy conservation is of secondary importance as opposed to sensor network where it is of prime importance, it is still a entity to be considered while the design of the MAC protocol along with the high QOS.

3.4.5 Ad-hoc robotic network architecture

![Ad-hoc robotic network architecture](image_url)

Figure 3.5 Extensive ad-hoc robotic network architecture
In the presented extensive architecture as depicted in Figure, the 802.11b standard is utilized for the wireless link. Here, the ad-hoc communication topology supported by 802.11 standard is employed. In ad-hoc communication, there is no infrastructure, and robot nodes are able to communicate directly to other nodes, with multi-hop routing support. The physical layer of 802.11 standard includes either frequency-hopped or direct-sequence spread spectrum communications in the 2.4 GHz frequency band. The MAC level architecture supports CSMA with collision avoidance, incorporating a contention window of backoff times when collisions occur. As collision detection is not possible, the nodes solve the hidden node problem by broadcasting RTS (request to send) and CTS (clear to send) packets. The architecture is a closed loop control system and data-centric network.

In the case when the robots route packets both control or data, these robots use the ZRP to route the packets amongst themselves. Also the ZRP is utilized in order to route packets between different robot zones within the ad-hoc network. An ad-hoc bridge, which uses, the NAT (Network Address Translation) in order to replace the robot node address with an Internet-routable when Internet connectivity is required. The Ad-hoc bridge here also allows the robot nodes to multi-hop communication and thus provides Internet connectivity. The IEEE 802.11 WLAN protocol specification do not define any support for multi-hop communication, especially in the link layer therefore, this constitutes as a challenge for the integration between nodes of the ad-hoc network. Thus 802.11 ad-hoc network is a major challenge since its protocol specifications has no definitions of multi-hop communication. Hence the ad-hoc bridge provides the multi-hop
communication required for the ad-hoc network. Hence the ad-hoc bridge thus facilitates the extension of the multi-hop range in the architecture.

### 3.4.6 Protocol layers in the extensive ad-hoc robotic network

![Diagram showing packet flow through protocol layers in Extensive Ad-hoc network](image)

The different protocols pressed into service for the underlying architecture are as follows.

1. A modified 802.11 MAC, which incorporates energy efficiency. The hidden node problem is also typical for nodes operating in the ad-hoc networks. Hence stress should be on to overcome the hidden node problem. Hence the 802.11 MAC needs to be designed taking into consideration these major issues.
2) UDP, which works in the Transport layer. UDP has been found to work better in ad-hoc networks. This protocol immensely helps to reduce overhead. UDP packetizes the data for transmission over IP.

3) IP, which works in the Network layer. IP is assigned with routing packets through the Internet. It can also fragment datagram to meet local size requirements and also reassembles them at the destination.

4) ZRP (Zone Routing Protocol), which resides in the Network layer along with the IP in the robot nodes. ZRP is a suitable hybrid protocol for ad-hoc networks hence this protocol is employed.

### 3.4.7 Swarm intelligence: Taking lessons from nature

Recently, biologists and computer scientists have studied to understand how “social animals” for instance group of ants, flock of bird, school of fish etc. interact, achieve goals and evolve. This gives rise to new kind of behavior termed “swarm behavior”. The resulting “swarm intelligence” is property of systems of non-intelligent robots exhibiting collectively intelligent behavior. This can be applied in optimization of variety of systems including robotics. In fact, swarm robotics is currently the most important application areas of swarm intelligence. Swarm robots provide the possibility of enhanced task performance and high reliability over traditional robotic systems. These robots can achieve some tasks that would be impossible for a single robot to achieve. Swarm robots are potentially reconfigurable networks of autonomous robots that are capable of coordinated sensing and interaction with the environment [16].
3.4.8 Pheromones messaging

Pheromones are chemical markers used by ants and termites for communication and coordination. Inspired by these pheromone messaging system, researchers have used a notion of “virtual pheromones” executed by message relaying from robot to robot. Virtual pheromones like their chemical counterparts facilitate simple communication and coordination and require little on-board processing. Virtual pheromones are transmitted at a known intensity, and their signal strength decreases linearly with distance. Receivers can reliably estimate distances on the basis of signal strength. A pheromone message is initiated by a source robot and is relayed from robot to robot throughout the group. This allows information to be extended all over the network in a spatially pertinent manner. This gives rise to a new paradigm of Pheromone Robotics. The robots in this paradigm are being called “pherobots”.

These pherobots are envisioned to play a crucial and useful role in search and rescue operation. In the event of a search for survivors in a building after a disaster, a group of pherobots are released at the entrance of the building. With the help of simple attraction/repulsion behaviors, these robots quickly disperse into open spaces. Upon detection of a survivor, a robot emits a virtual pheromone message signaling the discovery. This message is propagated locally between robots along unobstructed paths, producing a gradient as it is propagated. Ultimately, the message makes its way back to
the entrance where rescue team members can follow the pheromone gradient to the survivor [17].

3.4.9 Summary

The ad-hoc robotic network architecture is envisioned to perform tasks which are not possible to be carried out by single robot and also in the situation where cooperative behavior between robots is absolutely essential e.g. in search and rescue operation, in military operations like mine and cave searching. The architecture is conceptualized to provide the ad-hoc robotic network with Internet connectivity. Moreover, the architecture supports the multi-hop communication required for the robots to communicate amongst them and also among the robot zones. Hence, an efficient hybrid protocol namely the ZRP is utilized for routing between the zones and also within the zone. Another, important component of the architecture is the 802.11b Ad-hoc bridge which supports multi-hop communication. This is essential because the 802.11b specification alone does not support multi-hop communication. The ad-hoc bridge also uses the NAT in order to provide the local robot address with an Internet-routable address necessary for Internet connectivity for the robot nodes in the zones within the ad-hoc network. Moreover the MAC protocol is expected to be redesigned considering the high QOS requirements of the ad-hoc robotic network. Energy optimization is also awarded deliberation while building the MAC protocol. The strategies in swarm intelligence and pheromone messaging are envisioned to be exploited by the architecture. Such strategies are especially useful in search and rescue operations. Thus overall the architecture, addresses
at a higher level, the suitable components and the modifications required in order to support the paradigm of ubiquitous computing in the ad-hoc robotic network.

3.5 Sensor Network

3.5.1 Importance of sensor network

The time has come for transition from interactive to proactive computing. This is a decentralized and autonomous way of operation. The term decentralized is used here to emphasis the lack of central infrastructure. Also autonomous would mean that the external user interference is kept out. Proactive computers will anticipate our needs and take action on our behalf. Ad-Hoc Networks are the prime example of coming convergence of computing and communications. Small and inexpensive sensors based upon microelectromechanical system (MEMS) technology, wireless networking, and inexpensive low-power processors allow the deployment of sensor networks for various applications. Thus the capabilities of the sensor networks have increased with the convergence of wireless communications, digital electronics, and micro-electromechanical system (MEMS), facilitating the incorporation of sensing, signal processing and communication in one packaged sensor device.

Traditionally, the sensor network functioned as an open loop system. But, the self-organizing and self-configuring sensor network possessing autonomous sensing, computing, and communication system can be deemed as a closed loop system.
These self-organized sensor network find a wide variety of applications in areas like health, military and environment. In health, the sensor networks can be put into service to monitor patients and aid disabled patients. In military, these networks can be used for surveillance, reconnaissance and intelligence systems. In environment, the sensors can be used for remote environment, habitat, and also crop monitoring. On a higher note, these sensor networks will play a pivotal role in upholding the new concept of “Proactive Health” taking shape [18].

Wireless sensors represent a new generation of real-time embedded system with significantly different communication constraints than the traditional networked systems. Wireless sensors would work apart from everything else as “anticipators”. Sensors would work in a self-organizing and self-configuring network. The sensors are being created to be able to connect wirelessly and use minimal power. Providing Internet access to these sensors operating in the ad-hoc network is an excellent way to make them ubiquitous. These sensors apart from being able to exchange messages within the ad-hoc networks would also facilitate message exchange with the Internet nodes with the help of sink. These sensors run Ad-Hoc routing protocol to route packets within the sensor cluster or zone. They also run the wireless protocols designed for communication through the wireless channel. At the same time, Internet nodes also use this wireless protocol for communication with the sensor nodes through sink.
3.5.2 Wireless Sensor Networks

Wireless sensor networks are data-centric networks as opposed to MANETs, which are communication-centric networks. The sensor networks involve several attributes such as size of the sensors, communication environment, deployment, and energy availability. The composition of the sensors could be either homogenous or heterogeneous. The sensor networking is wireless in this particular case. Also the bandwidth is high for these networks. Moreover, the energy availability is constrained in this network.

3.5.3 Technologies for wireless sensor communication

For the ad-hoc sensor networks under discussion several technologies for wireless channel communication are available. Amongst them are the 802.11 standard, which are widely used for wireless LANs. Also for very high bandwidth requirements, an upcoming technology known as Ultra Wide-Band Radio (UWB) is also available. UWB has been used for baseband pulse radar and ranging system. UWB employs baseband transmission and thus requires no intermediate or radio carrier frequencies. The main advantage of UWB is resilience to multipath. Low transmission power and simple transceiver circuitry make UWB a good option for employment in sensor networks. Also for small range networks, Bluetooth is available. Bluetooth is an infrastructureless short-range wireless system intended to replace the cable between electronic user terminals with RF links.
3.5.4 UWB technology in sensor networks

The striking difference in the narrow band technologies and UWB, is that in narrow band technologies the spectrum occupies a bandwidth 10% or less than the center frequency and that in UWB, 25% than center frequency. An example of a specification using narrow band technology is 802.11b WLAN where the bandwidth is 22 MHz with a center frequency in the range of 2.4GHz. While in UWB, there exists a transmission with a bandwidth of greater than 500 MHz having a center frequency of 6GHz. Improved channel capacity is one major advantage of UWB. Sensor networks making use of several low-cost low-powered sensors. UWB therefore has the potential to provide enhanced value to the sensor networks. UWB radios could provide lower cost architecture than narrow band radios. Another key advantage of UWB is its robustness to fading and interference. UWB signals can be transmitted between 3.1 GHz and 10.6 GHz at power levels up to -41dB/MHz. UWB is capable of transmitting very high data rates using very low power. UWB technology is most useful in short-range (less than 10 meters) applications. This is due to the fact that FCC has mandated low power levels (-41dBm/MHz for legal UWB operation. Hence unless the legal power levels for UWB operation is increased, UWB is cannot be utilized in long-range application. On realization of the legal increase in the power levels, UWB can be extensively used in long-range sensor networks, especially in areas of habitat monitoring [19].
3.5.5 Resolution of identified problems and issues

The following are the identified problems and issues along with the resolution.

1) Security: The Wired Equivalent Policy (WEP) is used in 802.11 PHY based networks to protect link-level data during wireless transmission from eavesdropping and other attacks.

2) Fault Tolerance: The sensor nodes may fail due to lack of power, physical damage or habitat interference. The failure of sensor node should not affect the overall performance of the network. This is the reliability or fault tolerance issue. Fault tolerance is the capability to persist sensor network functionalities without any interruption due to sensor node failures. The decentralized approach followed in the sensor network architecture is expected to cope with the node failure problem.

3) Power Conservation: Power efficiency directly influences the network lifetime in a sensor network and is of pivotal importance. Due to the fact that sensor networks are highly energy constrained, the battery reserves cannot be feasibly replenished. Hence power conservation is of importance in order to prolong the network lifetime in a sensor network. Power conservation is achieved through random wake-up schedule during connection phase and turning the radio off during idle time slots. Another paradigm for power conservation in sensor networks is “data aggregation” whereby data coming from different sources is combined and routed to single destination along with elimination of redundancy and minimization of the number of transmissions thereby saving energy.
3.5.6 Roles of protocol layers

The physical layer addresses the needs of simple but robust modulation, transmission, and receiving techniques. The physical layer is responsible for frequency selection, carrier frequency generation, signal detection, modulation and data encryption. The MAC protocol needs to be power aware and be able to minimize collision with neighbors’ broadcasts. The MAC protocol in a wireless self-organizing sensor network achieves two aims. The first is the creation of the network infrastructure. The second is to efficiently share communication resources between sensor nodes. The network layer takes care of routing and data supplied by the transport layer. The transport layer is especially needed when the system is planned to be accessed through the Internet or other external networks. The communication between the remote Internet user and the sensor node is facilitated using transport layers like TCP or UDP. For the communication between the sensor node and the sink where all sensors route their data, the UDP protocol is preferable because of the limited memory available in the sensor node.

3.5.7 Need for Power-efficient MAC Protocol for Sensor Networks

Choice of a power efficient MAC protocol for successful operation of the wireless sensor network. As with all shared-medium networks, medium access control (MAC) is an essential technique that enables the successful operation of the network. Here a modified 802.11 MAC is put in service. As it is evident that sensor networks are
resource-constrained networks. Hence there is a dire need to design an energy efficient
MAC protocol. There are several major sources of energy waste. The first one is
collision. Retransmissions increase energy consumption. Collision increases latency as
well. The second source is overhearing, meaning that a node picks up packets that are
destined to other nodes. The third source is control packet overhead. Sending and
receiving control packets consumes energy too, and less useful data packets can be
transmitted. The last major source of inefficiency and energy waste is idle listening, i.e.,
listening to receive possible traffic that is not sent. The idle listening problem can be
handled by periodic listen and sleep. This way the robots can turn off their radios
periodically to enforce energy saving. During sleep, the sensor node turns off its radio
and sets a timer to awake itself later. This way the sensor node goes into periodic sleep
mode. For instance, in each second a node sleeps for half second and listens for the other
half.
3.5.8 Sensor network architecture

The main purpose is to provide a scalable and extensible architecture for the group of sensors in the network. Another intent of the architecture is to facilitate Internet connectivity to the sensor network. The Figure 1 depicts the Ad-Hoc Sensor Network architecture. The tiny sensors, which are employed in this network, are envisioned to be equipped with microcontroller, flash memory, SRAM, ADCs, peripheral interfaces, secondary storage etc. This is provisioned in order to enable the sensor for sensing and computation. These sensors are also equipped TinyOS which provide software support for the complete networked applications. TinyOS is a component-based runtime environment designed to provide support for deeply embedded systems, which require concurrency intensive operations while constrained by minimal hardware resources. The
TinyOS is an efficient event-driven operating system. It provides the basic mechanism for packet transmitting, receiving, and processing. TinyOS supports modularity, data sharing and reuse. These sensors run Ad-Hoc routing protocol to route packets within the sensor cluster or zone. The Internet nodes use UDP protocol for communication with the sensor sink. The sink is devoted to be the link between the ad-hoc wireless sensor nodes, which form a sensor zone and the Internet nodes.

In the sensor nodes, the network layer is divided into IPV4 and the Ad-Hoc Routing Protocol, which is ZRP in this case. The transport layer consists of the UDP. The reason being that it is being inferred that TCP is not suitable for Ad-hoc networks. The 802.11b protocol resides in physical and data link layer of both the sensor nodes and the Internet nodes. Moreover, the Internet nodes, obviously use only the IPV4 to route packets to the sensor nodes. The sensor nodes, when within the sensor zone use the ad-hoc routing protocol for routing packets. When the destination node is an Internet node then, the sink comes into play. The sink essentially needs to understand both the UDP/IP protocol and so also the Ad-Hoc Routing protocol. The sink also typically needs to be designed to handle the overhead resulting from packet routing. Also transmission delays also need to be minimized.

3.5.9 Summary

Present day sensor networks have the potentially find wide variety of applications in habitat and crop monitoring, and also in health monitoring which helps to support the concept of proactive health being conceived by researchers. The sensor network architecture is conceptualized with a higher goal of facilitating global accessibility for the
sensor nodes, which form components of the sensor network. Thus the paradigm of ubiquitous computing also holds good for the underlying sensor network architecture. The problems and issues concerning the sensor network are dealt with the help of respective implementations in the sensor network architecture. The sensors acting in the network are “smart sensors” with ability of sensing, computing, and communication. Such sensors deserve to be accessed globally by remote users in particular. Hence Internet connectivity to these sensor networks is of prime significance. So the architecture for the sensor network strives to achieve this goal along with other necessary system gains. The key problems and issues include the energy constraints of the sensor network, fault tolerance and the security. The power constraint problem is taken care by the employment of energy efficient MAC protocol design and also through other strategies for conservation of energy. The fault tolerance is incorporated inherently with the decentralized model of the architecture. The security issue is handled with the use of WEP encryption policy in the 802.11 standard to protect against link level attacks.
Chapter 4

Conclusion and Future Work

4.1 Conclusion

The framework for each of the existing scenarios provides a comprehensive architecture that defines all the essential parameters of the system. Thus each of the architecture serve as an incubator to design the relevant parameters of the system. The frameworks are envisioned to follow the best practices and abstract the system level details. Thus the architecture strives for a backbone and operational support for the robotic system and the sensor network as well.

The direct control robotic teleoperation defines the architecture for the direct control of the robot through teleoperation, which is essentially insensitive to Internet time delays. Further the selection of an operation framework parameters augments in achieving the goals for that mode of operation. For the supervisory control, the employment of an autonomous robot with local intelligence helps to cope with the Internet delay problem.

The ad-hoc robotic architecture performs multiple roles. The architecture provides for a modified MAC robotic protocol envisioned to be residing along with IP in the network layer in the ad-hoc robots. The modified MAC calls for energy efficiency
through techniques like periodic listen and sleep of the radios, which save considerable amount of energy which happens to be of high priority in “resource constrained” networks like the ad-hoc robotic networks. Also the architecture points out the need for a better routing protocol for routing between the ad-hoc robotic zone. Further the architecture also advocates the selection of UDP as the protocol in the Transport layer known for better performance than TCP in ad-hoc networks. Also the extension of architecture through the ad-hoc wireless bridge provides Internet service to the ad-hoc robotic network and aid in making the network universally accessible.

Finally the architecture for the ad-hoc wireless sensor networks provides the smart sensors with computing, sensing and communication capability with Internet connectivity to make the sensors truly ubiquitous.

The unified framework is thus envisioned, which consists of the three architectures namely the architecture for robotic teleoperation, the architecture for ad-hoc robotic network, and the architecture for sensor networks. The robotic teleoperation architecture is conceived as a network-centric architecture, while the ad-hoc robotic architecture is conceived as the communication-centric architecture while the sensor network is considered as the data-centric architecture. This apparently signifies that the problems and issues concerning each of these architecture is quite varied and diversified. Hence each of the architecture is orchestrated around the problems and issues concerning the relative system. The problems and issues haunting all these three systems include the low QOS, time-delay problem of the Internet, delay and jitter, fault tolerance, security, energy conservation in case of sensor networks, insufficient bandwidth and low throughput. Each of the architecture strives to implement solution for each of the
problems and issues applicable for the individual system. Hence the architecture acts as a wrapper around the system to cope with the problems and issues. The unifying factor for these three architectures is the Internet. So at the core of the framework lies the Internet, the communication medium which is potentially render the components of each of the architectures globally accessible and can reach out to innumerable users. Also the components also could communicate with their counterparts in the other architecture via the Internet. Hence the underlying framework immensely helps to uphold the paradigm of ubiquitous computing and communication for the robotic and sensor networks of the architecture.

4.2 Future Work

The following are the highlights about the probable work in the future as part of the follow up of the endeavor in the current thesis area.

1) Designing modified MAC Robotic Protocol for ad-hoc network based on the framework requirements for the ad-hoc robot network as well as the ad-hoc sensor network. The important considerations while designing the MAC protocol would be energy efficiency since the nodes, robots or sensors operating in the ad-hoc network are energy constraint in the sense that the frequent recharging of such nodes has been found to be infeasible. Also development of a suite of protocols that support mobile node interaction including MAC and network level design.
2) Simulation of the Framework Testbed. Simulation provides a facility to study the network conditions like packet flow, time delay parameters, and round-trip time. The study of large number of nodes e.g. 500 nodes in a physical testbed is difficult, costly and not feasible. Hence the simulation provides a good alternative as a testbed for the framework. The tool available for the simulation of ad-hoc sensor networks are the customized m-files created in MATLAB. The screen shot of the simulation is shown in Figure 4.1. Also a freeware available for ad-hoc wireless network simulation is NS-2.
A typical tool is the Robotics toolbox for MATLAB [20] is available. The toolbox allows a MATLAB users to readily create and manipulate datatypes fundamental to robotics such as homogenous transformations, trajectories, functions provided for manipulators which include forward and inverse kinematics, Jacobians, and forward and reverse dynamics. The toolbox for the Puma 560 6 DOF robot manipulator is as shown in Figure 4.2.
Figure 4.3 Screen shot of the simulation of Aibo robot using the Webots 4.0.1.4

4) Webots 4.0.1.4 is mobile robot simulation software. It consists of a prototyping tool allowing user to create 3D virtual worlds. The robots can have several locomotion schemes like wheeled robots, flying robots, legged robots. The robots can also be equipped with a number of sensors, cameras, grippers etc. The user can thus program each robot individually to exhibit desired behavior.

5) Conceptualization of Swarm Intelligence in Ad-hoc robotic networks in order to enhance the overall efficiency of the network. The brilliant concepts of swarm intelligence can be potentially applied in ad-hoc network to accord topology advantages for the network. Execution of physical test bed for ad-hoc robotic
network with the use of readily available robot components like cybot robot kits. The wireless setup like 802.11 is also available [21].

6) Exploring UWB radio as the underlying technology for the wireless robotic and sensor networks. This technology promises to be a better alternative especially in sensor networks where low power sensors are in need for a wireless technology, which would cater to their energy-constrained physical structure and requirements. However currently UWB could be applied only to short-range sensor networks typically up to 10 meters. This is due to the restrictions imposed by FCC on the legal power level operation in UWB. UWB therefore can be applied in long-range sensor networks when FCC approves an increase in the legal power levels for UWB operation. The UWB technology provides the means of integrating the very best of radio communications, radar and location sensing technology into a solo system.
LIST OF REFERENCES


