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NETWORK ENABLED POWERED WHEELCHAIR ADAPTER KIT (NEPWAK)

by

Ankit Arora,
B.Tech, Electronics and Communication Engineering, India, 2002

A thesis

presented to Ryerson University

in partial fulfillment of the

requirements for the degree of

Master~~s~~ of Applied Science (MASc)

in the program of

Electrical and Computer Engineering

Toronto, Ontario, Canada, 2006

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NETWORK ENABLED POWERED WHEELCHAIR ADAPTER KIT (NEPWAK)

Ankit Arora
MASc (2006), Electrical and Computer Engineering
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Due to the aging population of many developed countries, the call for accommodation for the handicapped, and the elderly are being addressed on political, industrial, and scientific fronts. We believe that, in the near future, rehabilitation robots will become a significant component of health service systems in the world.

Rehabilitation robotics involving the use of powered wheelchairs as mobility platforms has taken place in many research groups with various goals. We have taken one such initiative; we have sought to develop a kit that can be retrofitted to any commercial powered wheelchair augmenting it with remote health care and control. We call this system "NEPWAK–The Network Enabled Powered Wheelchair Adapter Kit". NEPWAK will provide mobility and remote health care to individuals who otherwise could not independently use a standard wheelchair due to motor, sensory, perceptual, or cognitive impairments. To ease the task of remote operators in transporting patients, NEPWAK incorporates human tracking and following capabilities, and an obstacle avoidance system.

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Chapter 1 Introduction

1.1 Introduction to NEPWAK

Common industrial robots usually perform repeated movements with great speed and precision in an exactly defined environment. In contrast to them, service robots carry out supporting tasks for humans in unconstrained environment. One potential target application for service robots is their use as assistive devices for rehabilitation of physically challenged and elderly people.

Rehabilitation robotics is still in its infancy but is a growing area of research. We expect that, in the near future, rehabilitation robots may become a significant component of health service systems in the world. The application areas of rehabilitation robots are continuously expanding to new dimensions that aim at improved assistance in different kinds of activities for people with disabilities and the aged. By compensating for the specific impairments of each individual, rehabilitation robots enable handicapped people to live more independently and with greater mobility than they could ever before.

Rehabilitation robots, such as smart-wheelchairs, have gathered interest from many research groups. Research involving the use of powered wheelchairs as mobility platforms has taken place with various goals. Many endeavours relate to

augmenting the mobility of the chair's occupant through the use of sensors providing input to on-board semi-autonomous or fully autonomous control systems. Our research, however, focuses on using wheelchairs as platforms for remote health care provisioning and remote control.

We have sought to develop a kit that can be retrofitted to any commercial powered wheelchair augmenting it with remote health care and control. We call this system NEPWAK–"The Network Enabled Powered Wheelchair Adapter Kit".

NEPWAK will be developed to provide mobility and remote health care to individuals who otherwise could not independently use a standard wheelchair due to motor, sensory, perceptual, or cognitive impairments. It will introduce techniques for modifying and using commercial powered wheelchairs as mobile platforms enabling communication and remote control. The wheelchair will run a Single Board Computer based embedded server allowing a remote health care provider to connect through both workstation and mobile computing clients. The remote health care provider will receive live audio, video and other sensory feeds, and will be able to remotely manoeuvre the wheelchair under certain circumstances.

To facilitate the use of NEPWAK wheelchairs in clinical and extended care environments, we shall also incorporate human tracking and following capabilities in NEPWAK that will ease the task of remote operators in transporting patients.

1.2 Why NEPWAK?

Due to the aging population of many developed countries, the call for accommodation for the handicapped, the immobile and the elderly are more and more being addressed on political, industrial, and scientific fronts. Recent developments in fields as diverse as computer science, robotics, wireless communications, and sensory technology allow us to significantly broaden how we may address accommodation in our broader society.

As populations in first world countries grow older, providing assistance to increasing numbers of people in retirement or extended care facilities is rapidly becoming problematic [1]. There simply are not enough facilities, nor are there sufficient personnel to provide the services necessary for an ever-aging population. Many governments hope to reap the benefits of encouraging the elderly and the disabled to live independently as much and for as long as possible [2-4].

Technology has also long promised to enable elders to postpone moving into institutional settings by providing more convenience, safety, mobility, and communication. A number of studies [5] have sought to examine the application of technology to assist and aid elderly persons in their homes, making it possible for them to live independently for a longer period of time. Typically this approach involves the use of Independent Life-Style Assistant (ILSA) prototype [6-8] which monitors the daily activities of elders through a variety of sensors to identify functional decline as an indicator of imminent health concerns. Caregivers use the Internet, telephone, and email technologies to check the status of the elders under their care at any time, while the system can self generate alerts via telephone and email with important elder status updates. By alerting caregivers to potential health concerns, ILSA hopes to prolong elder independence at home and improve caregiver effectiveness and experience.

NEPWAK is one such initiative to provide "on demand" services that allow interaction with and assistance from remote care providers. Currently, such services are intermittently available through visiting nurses, friends, relatives and similar aides. For example, an area where an individual might need assistance is in particularly difficult spaces, such as might be found when manoeuvring a wheelchair through a particularly tight passage. Another potential scenario involves remote care providers monitoring a wheelchair owner through onboard medical sensors like pulse monitors or other biometric devices. This could be

done continuously or during certain activities such as the administration of medication. Let us consider a few scenarios to better understand the need for NEPWAK in today's world.

In nursing home setting, a resident may have limited mobility as a result of an accident. She may also experience occasional seizures or suffer from any number of chronic conditions that could occasionally lead to loss of self-control or the need for immediate assistance. The resident enjoys daily trips around town in her electric wheelchair. The wheelchair has been equipped with a NEPWAK. A remotely located nurse can monitor the resident on her daily trips through a pan-n-tilt onboard camera and a duplex audio link. If the resident were to experience a seizure, the remote nurse can override the wheelchair's control and drive her out of a dangerous situation or drive the wheelchair to her if she is incapacitated.

A person lives in a small town and has been using electric wheelchairs for at least fifteen years. In fifteen years, she has owned three wheelchairs. They simply do not last more than five years because regular maintenance is nearly impossible. To get repair work done, she must send the chair to a repair center, 300 miles away. Then she must wait, sometimes weeks, before her chair is examined. NEPWAK equipped wheelchairs could avoid this problem. For instance, wheelchair service centers could perform periodic inspections of wheelchairs in rural locations. Service technicians could perform remote

diagnostics allowing for preventive action. Problems could be detected early, parts ordered, and an appointment scheduled for repair. All this could be achieved with a minimum amount of inconvenience to the user.

Patient transportation in health care facilities is a rising problem [9]. Physically challenged patients who cannot use a powered wheelchair have to be transported in manual wheelchairs requiring additional staff simply for moving chairs. The problem escalates when such patients require the use of an oxygen concentrator. An oxygen concentrator is a machine that delivers high quality air to a patient. The device, which is on casters, is approximately 1.5' x 1.5' x 2.5' and weighs about fifty pounds. Attachment devices that allow the staff to push the wheelchair and the concentrator as one unit are available; however, it is physically a very challenging task to push the units together. Use of powered wheelchair does not solve the problem as they do not have remote control capabilities. However, NEPWAK equipped wheelchairs could effectively address the problem. Medical staff carrying Wi-Fi enabled PDAs can form an ad-hoc connection with the wheelchair and can conveniently provide remote control.

Transporting patients over extended distances this way is problematic for nurses. Controlling the wheelchair through the PDA's touch-screen Graphical User Interface (GUI) while walking alongside can be very challenging. It is here where NEPWAK's novel human tracking and following capability can provide semi-

autonomous assistance to a care provider. NEPWAK will allow the wheelchair to follow the provider through corridors and within rooms--greatly easing the task of transporting patients.

An important concern however is the adoption of handheld computing devices by medical professionals as a data acquisition and medical telemetry tool. According to [10], Mobile computing is the next technology frontier for healthcare providers. Data capture and retrieval using a PDA by physicians, nurses and allied healthcare professionals, are enhancing patient care and improving efficiency. Recent data from the American Medical Association/Forrester Research 2005 Physicians And Technology Study [11] of 1,331 US physicians show (Figure 1.1) doctors as technology-savvy gadget grabbers - at least compared with the average consumer. At 57%, US doctors, as a group, are nearly five times more likely than the general US consumer to have a handheld computing device. At the same time with the introduction of the 802.11b wireless standard [12], in-building access points have become increasingly common within many buildings. In parallel, evolution of EV-DO [13] CDMA 'Internet everywhere' networks is providing unparallel connectivity for emerging service robotic applications like NEPWAK.

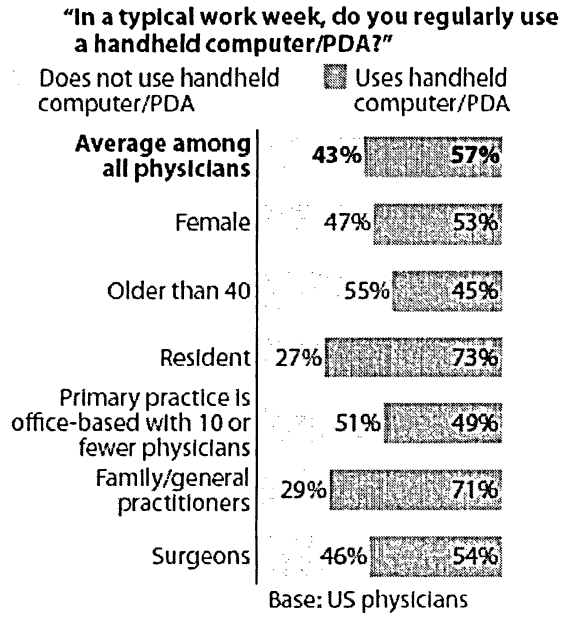

Figure 1.1: Use of handheld computer by medical professionals

1.3 NEPWAK Conceptual System

NEPWAK relies on existing wheelchair technology components. In essence, we have attempted to retrofit existing differential drive wheelchairs with telebotic[1] components designed as service enhancements for the chair's occupant. The wheelchair is equipped with a Single Board Computer (SBC), a pan-n-tilt video camera, microphone, peripheral IR sensors and a WiLAN network card (Figure 1.2).

---

[1] Telebotics is the area of robotics that is concerned with the control of robots from a distance, typically using wireless connections (like Wi-Fi and similar).

The SBC runs a custom server application that allows both workstation and handheld computing clients to connect in either infrastructure or ad-hoc mode. The clients receive audio (full duplex), video and other sensory feeds from the wheelchair. Through an easy and intuitive Graphical User Interface (GUI), the remote operator is able to manoeuvre the wheelchair or pan-n-tilt the onboard camera to inspect the surroundings or the wheelchair's occupant. NEPWAK's novel human tracking and following system allows the wheelchair to track and follow the care provider carrying a Wi-Fi enabled handheld computing device, thus greatly easing patient transportation. The NEPWAK's modular architecture also allows connecting medical sensors like pulse-rate monitors or temperature sensors for medical telemetry.

NEPWAK therefore transforms electric wheelchairs as mobile communication platforms for remote control and remote monitoring through audio, video and other sensory feed.

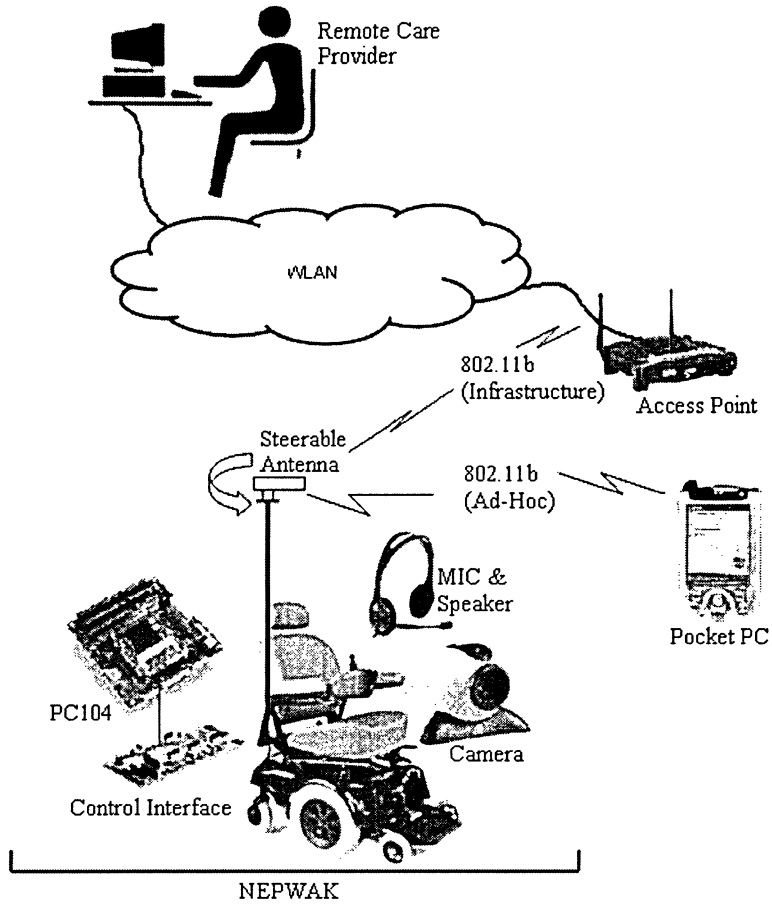

Figure 1.2: NEPWAK architecture overview

1.4 Research Goals

1.4.1 Augmenting electric wheelchairs with telebotic capabilities

The main objective of this research is to explore the possibility of transforming electric wheelchairs into a communication platform for provisioning of remote care, monitoring and remote control services. The notion of providing remote control and assistive services to disabled mobile individuals is novel. Our

approach involves the reuse of familiar technologies in the form of electric wheelchairs, commercial cameras and microphone systems, and sensor arrays unified under a software architecture supported through a wireless network. The goal is to design and develop a kit – "Network Enabled Powered Wheelchair Adapter Kit" that can be retrofitted to any commercially available powered wheelchair augmenting it with telebotic components such as video, audio and remote control and local autonomous services such as obstacle avoidance and person following.

We seek to develop both workstation and PDA clients for NEPWAK. The audio, video and control telebotic components will be primarily designed for 802.11 b/g WiLAN networks. But the architecture will be extensible to any wireless network.

1.4.2 A novel human tracking and following system

Much work in the field of person tracking and following is based on vision systems. However, the biggest problem that haunts a vision-based person tracking and following system is that of target discrimination.

How does a mobile human-following robot differentiate people wearing similar clothes?

Using dedicated active beacons carried by humans is a possible solution that is not widely supported, as beacons are considered intrusive. In this thesis, we will

explore the possibility of using a handheld wireless device as an active beacon. We prove that a Wi-Fi handheld device can be accurately located by a steerable directional waveguide antenna, thus solving the target discrimination problem. Once the target is located, we believe that a vision-based system is capable of providing accurate distance measurements. Thus, our approach shall use the fusion of pose data from our novel Wi-Fi-based technique with a vision-based system to generate an accurate and robust person tracking and following system. The most ambitious goal of this research is to allow human following at a person's natural walking pace of approximately 1.4 m/s.

1.4.3 User interface for teleoperation

The thesis will also address a human interface for NEPWAK's Workstation and Handheld clients. The goal is to design a user interface that will allow medical staff with little or no knowledge of NEPWAK's underlying architecture and technology to intuitively and conveniently operate the system. Towards this goal, a summary of views and comments about NEPWAK from prospective users and medical practitioner's will be presented.

1.5 Thesis Organization

The rest of this thesis is structured as follows:

Chapter 2, Literature Review provides background information related to the thesis including the current state of research. Research in areas of telebotics, smart wheelchairs, human tracking and following, audio/video over IP networks, and IP Mobility will be reviewed.

Chapter 3, NEPWAK Architecture and Operation will present in detail the hardware and software architecture of NEPWAK. Tele-operation and human following techniques implemented will be discussed.

Chapter 4, Development Stages and Experimental Results will present the three development stages of NEPWAK, the experimental results and lessons learned at each stage.

Chapter 5, Conclusions and Future Work will provide a summary of the work completed, results achieved and will give suggestions for future improvements.

Chapter 2 Literature Review

Robotics has always been considered an interdisciplinary science as it brings together concepts in computer science, various engineering disciplines, and cognitive psychology to name but a few. To understand, design and develop our "Network Enabled Powered Wheelchair Adapter Kit" (NEPWAK), we have used material from many fields of endeavour. In this chapter we will present work from various sources broadly covering the following areas:

- Rehabilitation Robotics
- Smart Wheelchair Technology
- Tele-robotics (Telebotics)
- Audio and Video for Telebotics
- Human Computer Interaction (HCI) and Graphical User Interface (GUI) for telebots
- Human Tracking and Following for mobile robots
- IP Mobility

2.1 Rehabilitation Robotics

The discipline of Rehabilitation robotics is diverse, and although the definition of each word is well understood, the intersection of the two areas is still small and the field embryonic. The situation however is rapidly changing. Developments in

robotics and computing, together with an increasing need to develop tools for assisting individuals with daily living tasks is driving the potential of the field to help people. This is especially true in allowing the potential of greater independence to the elderly.

The development of rehabilitation robotics dates back to the latter half of the twentieth century. The first referenced rehabilitation robot was the Case manipulator [14] constructed in the early 1960's. This was a powered orthosis with four degrees of freedom (DOF), which could move a user's paralysed arm. Work in the more specific area of rehabilitation robotics started in the mid 1970's. One of the earliest projects was the workstation based system designed by Roesler [15] in Heidelberg, West Germany. The arm of this system was based around an electrically powered prosthetic arm, mounted on a horizontal track. Various items of equipment were laid out on the simple but cleverly designed workstation table and could be manipulated by the arm using pre-programmed commands. Although the use of robotics is intended to bring flexibility, the workstation approach is itself limited. A fixed site robot arm can only interact with objects arranged (by an able bodied person) around it. The idea of using a mobile robot is therefore very attractive, and the use of mobile assistive robots for rehabilitation purposes has gained a lot of attention.

One of the earliest projects attempting to use a mobile robot in a rehabilitation setting was the MoVAR (Mobile Vocational Assistive Robot) project at Stanford University [16]. A small Puma industrial arm [17], equipped with a video camera to allow operation in another room, was mounted on an omni-directional mobile platform. Although convenient for some recovering patients, controlling such a robot would not be possible for patients with reduced motor skills.

The use of a manipulator mounted on an electric wheelchair which moves with the user, has also been explored. The Manus [18] wheelchair mounted manipulator is one of the successes of rehabilitation robotics and has been sold commercially by Exact Dynamics since 1990. It is a general-purpose manipulator with six DOF and a two-fingered gripper. Another wheelchair mounted robot which is currently commercially available is the Raptor arm, from the Rehabilitation Technologies Division of Applied Resources Corporation (RTD-ARC, New Jersey, US) [19]. The Raptor is much simpler than Manus, having 4 DOF and gripping that allows individuals with disabilities to reach objects on the floor, on a table, or above their heads. While having less functionality than Manus it is also significantly cheaper.

These rehabilitation robots serve useful purposes as prosthetic and orthotic devices. However, they do not address the need of patients who cannot operate electric wheelchairs and add-on assistive devices due to motor, sensory,

perceptual, or cognitive impairments. Our goal is to provide assistance to such people by transforming electric wheelchairs into communication platforms, providing control, audio and video services as well as enabling them for medical telemetry services.

2.2 Smart Wheelchair Technology

Research involving the use of a powered wheelchair as a mobility platform has taken place by various research groups with many goals. A representative list would include:

- The NavChair project – University of Michigan [20]
- The Wheelesley project – MIT [21]
- The Deictic Wheelchair – Northeastern University [22]
- The TinMan project – KISS Institute of Practical Robotics [23]
- TAO – Applied Artificial Intelligence Inc. [24]

The European smart wheelchair community is represented by – SIAMO, Spain [25]; the CALL Centre, Scotland [26]; the SENARIO, Greece [27]; and the RobChair, Portugal [28] projects.

The concept of a "smart" wheelchair involves augmenting the mobility of the chair's occupant through the use of sensors providing input to on-board semi-autonomous or fully autonomous control system. Typical of this approach is [20]

demonstrating a low-cost robotic system in their "Tin Man" project. The system allows a rider to use various modes of control that employ several "behaviours" to navigate in an indoor environment.

The "Wheelesley" project demonstrated a system with the goal of creating a complete robotic navigation system for both indoor and outdoor movement. The "NavChair" system was developed with the goal of providing mobility to people who are unable to drive a standard wheelchair. To accomplish this, the system employs automatic obstacle avoidance, wall following and door passage navigation techniques.

In order for the smart wheelchairs to be safe and reliable, so as to have a better chance of being accepted by their potential users, they are designed to be semi-autonomous. That is, they are able to carry out certain tasks on their own, but they have to rely on the human operators for a higher level of control and monitoring. Thus, a smart wheelchair is a highly interactive system which is jointly controlled by the human operator and the robot's software. That is why the design of the human-machine interface is a key issue in the development of a smart-wheelchair. Some projects [24, 28] employ a speech recognition system to enable the user to issue commands by voice. In the Wheelesly project, the human operator controls the wheelchair by choosing high-level commands via a graphical user interface on a notebook computer. The SIAMO project provides a

variety of interactive devices – adaptive joystick control, voice recognition, sip-and-puff system [29], head movement navigation system etc.

Another major concern that has to be taken into account when designing a smart wheelchair is that of safety. As service robots in general operate in the direct vicinity of humans, their malfunction could cause severe harm to people. Therefore, such robots have to be considered as safety-critical systems [30]. For smart wheelchairs this classification is even more reasonable because they transport individuals who completely depend on the correct functioning of the system. A necessary safety feature implemented on smart wheelchairs is object avoidance through the use of sensors like sonar and infrared.

Commonly sonar sensors are mounted in a ring around the wheelchair, but sometimes they only cover the front of the vehicle like the Navchair project's design. Infrared sensors are also widely used, for example within the Robchair, wheelesley and TAO projects. NEPWAK makes use of Infrared sensors in the front and behind the wheelchair to provide a reactive object avoidance system. We also provide an infra-red sensor to monitor the ground surface just ahead of the wheelchair so as to avoid falling down stairs or running into a ditch.

A problem in shared control so-called 'mode confusion' [31] always arises if a human operator and a technical system are jointly in charge of control. NEPWAK

addresses this problem by providing a hierarchy in the control system. The design allows the local wheelchair joystick to exercise the highest level of control and can override the remote control and the object avoidance system. Next, at a lower priority is the object avoidance system with the remote control system having the lowest priority. In this way NEPWAK avoids mode confusion and provides safety against possible human errors during remote control.

As discussed, the concept of smart wheelchairs primarily revolve around augmenting the mobility of the chair's occupant through the use of sensors providing input to a local on-board semi-autonomous control system. However, recently, provisioning of telebotic components such as remote control and monitoring on smart wheelchairs has also seen considerable research activity [32, 33]. But despite of the convincing progress the smart wheelchair community has shown, there is still a lot of work to be done before such devices can achieve commercial success.

2.3 Audio and Video for Telebotics

Telerobots, teleoperators, and remotely operated vehicles belong to a class of machines used to accomplish a task remotely, without the need for human presence on-site. They are typically used in situations that are too hazardous to humans like the pressure of deep water, the vacuum of outer space, or toxic

environments commonly found in many industrial environments. A growing number of telerobots are used for applications where it would be too expensive or too time-consuming to send humans, for example in telemedicine or telemaintenance that require highly trained individuals with special skills. The human operator supervises the telerobot through a computer intermediary. The operator provides to the computer, information about goals, plans, and orders related to a remote task, getting back integrated information about accomplishments, difficulties and sensory data. The telerobot executes a task based on the information received from the human operator plus its own artificial sensing and intelligence.

There are many cases when there is a need to control a mobile robot from a remote computer. Teleoperation has many possible applications from search and rescue to bomb disposal [34-36] and today, the need for assistive robots for the severely handicapped and the elderly is increasingly being recognised [37]. The interaction between the user and the robot typically happens through a graphical user interface. Therefore, an appropriate user interface would help to improve the relationship between an inexperienced or reluctant user and the advanced technology. Feedback to user commands in such an interface can be provided in a number of different ways. For example some text about what the robot did. The most effective feedback appears to be a video stream received as an output from a video device installed on the robot. The video feedback creates a sense of

being present at the remote site and allows a satisfactory degree of technical performance; this is referred to as telepresence [38].

The rapid proliferation of Wi-Fi networks [39], deployment of broadband networks and the availability of cheap digital cameras have led to the development of many telerobots using audio and video feedback for teleoperation [40, 41]. Despite all the applications, the human-experience during teleoperation is far from "being there". Capturing, processing and streaming digital video for real time teleoperation is very challenging and computationally expensive [42]. Therefore efficient compression is needed to reduce bandwidth and storage space. Video compression is accomplished by taking advantage of the similarities or redundancies that exist in the digital video data. Within a single frame, there are spatial redundancies as nearby pixel values are often correlated. That is, the value of any given pixel may be predicted by the values of its neighbours. There are temporal redundancies between adjacent frames in video as well, as they often contain the same objects [43]. Video compression also exploits the fact that the human visual system is limited and can be fooled. Therefore, only relevant features that can be perceived by the human eye are coded.

For teleoperation purposes, streaming individual images or snapshots instead of streaming small video segments has some significant benefits [44]. Each snapshot is an individual image that is sent to the client as a frame. The rational

behind using individual frames instead of segments of video is speed. Recording a video segment and streaming the result yields playback delay as compared to streaming single snapshots. Thus, this technique - pioneered within the N-CART lab [45] - is well suited for real-time teleoperation purposes. In addition, the use of individual images allows the server to send the image only when the client requests it. This way the server can skip old frames if the client can not display the images fast enough. Hence the server can adapt to clients with different connection speeds and the client can always display the most up-to-date image.

For audio streaming however, the situation is very different. Single audio snapshots are not usable. Research has shown that humans are quite tolerant to 'jittery' video while a smooth audio streaming is required for speech recognition [46]. Therefore, audio has to be recorded for a short period of time (typically 200ms) and then streamed. Streaming audio and video separately however produces another problem - asynchronicity. The server, client or the network can produce variable delays between the streams as a result the audio and video can loose synchronization. [44] Suggests the use of the audio stream as the master stream and the video should be "rolled-back" to match with the audio segment, hence synchronizing the two streams. While, in practice, this solution often works quite well, it may lead to unacceptable delay for the control task to be performed safely under lower bandwidth conditions.

We understand the importance of audio-video synchronization in some applications, such as streaming pre-recorded video or live TV on IP networks [47]. However, we oppose to the idea of synchronizing audio-video for real-time teleoperation. Since audio stream always lag the video as it requires recording for a short interval before streaming (typically 200 ms), the video has to be slowed down to match the audio. This produces an unnecessary delay in video streaming. We believe that for a real time teleoperation video is the most important feedback service for the client, therefore delay in video should be kept to a minimum. Reliability and safety of teleoperation is much more critical than media synchronization.

2.4 Human Robot Interaction and Graphical User Interface for Telebots

Human Robot Interaction (HRI) and the design of a Graphical User Interface (GUI) are key issues in the development of any safety critical robotic system especially service robots for the elderly and disabled. The emerging variety of handheld computing devices such as mobile phones and personal digital assistants, are challenging our established practices for user interface design.

On a mobile device, the means for interaction are very limited; the screen is very small and there are only a few buttons instead of a complete keyboard.

Moreover, the fundamental characteristic is that such devices can be used while being mobile. This implies that designers cannot expect users to devote their full attention to the operation of the device. Apart from these limitations, however, today's handheld computers potentially offer users--detached from a stationary workplace--the power of information processing and communication. Thus a strong motivation exists for addressing the HRI issues inherent in mobile technology in order to exploit the potentials of mobile computing better.

The design of user interfaces for mobile devices impose several challenges on interaction design. Screen area is very small due to the limited physical size of the device, stressing the design of graphical interfaces [48] and forcing designers to explore the use of new means of output. The use of sound is being carefully investigated in [49-51]. Correspondingly, interaction with mobile device interfaces is limited due to handheld operation forcing designers to explore new means of input such as gestures [52], speech [53], environmental sensors [54] and context awareness [55, 56].

Examining the literature on mobile HCI, it is clear that new constraints and approaches should be carefully considered in order to create useful applications employing mobile devices. Many issues arise when designing a handheld computing-based interface. The screen size is limited; therefore it is hard to display all useful information simultaneously. In a typical example of a medical

service robot equipped with audio-video streaming capabilities, the handheld client should be able to display:

- Video,
- Sensory feedback,
- Motion control interface,
- Medical telemetry information and
- Menus for customizing settings according to individual needs.

It is very challenging to accommodate all this on the small screens of handheld computers. On the other hand, interfaces designed for desktop or laptop computers are able to simultaneously display a large amount of information but are not easily transported in ones pocket. The interaction modes with standard computers include mouse and keyboard interactions, and potentially speech, this is currently not possible with handheld computers.

For NEPWAK we make use of an iPaq PocketPC as the remote handheld client. Our approach to the GUI design is presented in chapter 3. We have observed that stylus-based interaction is not practical for many users as it is difficult to use a stylus while walking or running. Additionally, a stylus is small and can easily be lost or misplaced. Speech-based interaction is not always practical, as it requires a verbal communication link between participants; relies on voice recognition

technology to make exact word matches without error; and may not be feasible in all situations.

Providing voice commands in cluttered, noisy environments as well as situations when noise is not permitted hampers the use of speech-based interfaces. We have therefore followed a different approach to HRI. We have equipped NEPWAK with human tracking and following capabilities allowing it to follow a human. This allows the walking human to lead the NEPWAK equipped wheelchairs without interacting directly with the hand-held device. The operator however can take over remote control at anytime based on need.

2.5 Human Tracking and Following

The need for tracking and following a person with a mobile robot arises in many different service applications. Scenarios for a manned mission to Mars call for astronaut extravehicular activity teams to be accompanied by semi-autonomous rovers. These rovers must be able to safely follow the astronauts over a variety of terrains with minimal assistance [57]. Another application is the use of mobile robots as tour guides in scientific laboratories or museums [58]. Potentially, even something as simple as, a tool cart following a mechanic might prove desirable.

Much work in the field of person tracking and following is based on vision systems using stationary cameras [59]. Most of the work originates from virtual reality applications where a person moves in front of a stationary background. The motion is detected by subtracting two subsequent frames [60, 61]. These techniques are typically not suitable for human tracking from a mobile platform since both human and platform are mobile at the same time and the background will be constantly varying. An interesting colour-based system which is able to track coloured blobs in real-time is presented in [62]. It is implemented on a mobile robot which locates a person in dynamic environments but requires wearing a uni-colored shirt with one of four predefined colors. Since their approach does not rely on static environments, is robust and works in real-time, it is very promising for our purposes. However, a major drawback of the system is in distinguishing one human from another if both are wearing the same coloured shirts.

Tracking people based on laser data is becoming ever more popular because of its accuracy and speed of processing, especially compared to traditional vision systems [63-65]. Although a very good sensor, a big disadvantage of employing a laser is that it requires the target to be within range and line of sight and the problem of target discrimination persists.

Human tracking techniques employing active beacons [66, 67] (Infrared, Ultrasonic etc.) on the human body are simpler but not a very popular approach. They are considered 'intrusive' since they require people to carry a dedicated beacon device. Their biggest advantage however, is that they greatly simplify target discrimination as each beacon can transmit a unique identifier signal. The approach taken in NEPWAK is similar except that the chair's occupant (leaving the chair) or medical staff carries a PDA instead of a dedicated beacon. We believe carrying a PDA is not as intrusive as single function beacons as at least they have the potential of providing additional functionality. With the advent of Wi-Fi technology, PDAs are commonly used as mobile telephones, medical information systems [68] organizers and also as entertainment units. NEPWAK functionality would simply be an additional service to an already existing need.

To date, we are unaware of any investigation focused on human tracking and following using Wi-Fi devices as either sensors or beacons. However there has been considerable research in the field of location estimation of mobile robots based on Wi-Fi received signal strength (RSS) maps, [69, 70] being typical. Generally, the technique involves building the RSS maps by profiling the site. Then, for location estimation, the client reports its RSS measurements that are compared against the RSS model to locate it.

Person tracking with a mobile robot is a highly dynamic task and fraught with difficulties. The sensory environment of a human subject is constantly changing as both the human and the robot are, or could, be moving. Some researchers have fused data from multiple sensors for human tracking. For example, [63] tracks people based on vision and laser range data. In [71] data queues from Laser, GPS and stereo vision are fused to obtain the final pose. Our approach is similar in the sense that we fuse pose data[1] queues from two independent tracking systems – a Colour-based image processing technique and a Wi-Fi based technique to achieve a highly accurate and robust tracking system. The Wi-Fi based approach provides a region of interest (ROI) which is confirmed by the colour-based technique and then the distance of separation is calculated by using the height of the colour blob in the ROI. Details are discussed in Chapter 3.

2.6 IP Mobility

IP Mobility is the concept that allows users carrying Wi-Fi enabled handheld computers or other IP-enabled devices to stay connected with the network as they move from one IP network to another. In our NEPWAK trial system, network access was provided by an IEEE 802.11b Wireless Local Area Network in

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[1] The data that provides a measure of the position of the object. In our system we use the ROI and Distance as the pose data of the person being followed by the robot.

infrastructure mode and connected to Ryerson's campus network. We established client-server communication between the remote controller (acting as client) and the wheelchair's Single Board Computer (SBC) (acting as server). The SBC server communicated with the controlling client via a fixed IP address--valid across the entire campus. As the wheelchair moved beyond the radio range of one Access Point (AP), and entered the range of another AP, it had to change its point of attachment to the network. This re-association from one access point to another is known as Handoff. Handoff can make the difference between effective & safe control of the wheelchair and the possibility of leaving the wheelchair & its occupants stranded.

In our NEPWAK trials, a single IP address is maintained because the APs are connected through a distribution system (typically connecting the APs via Ethernet bridges) on a virtual LAN (VLAN), which is connected to a single router at the edge of the campus network. Thus, all the APs belong to the same Extended Service Set (ESS). The handoff between APs occurs at the link layer only, and remains transparent to the network layer (Figure 2.1). In a large network divided into subnets, the wheelchair's IP address may become topographically invalid. In such cases, when the wheelchair moves to a different IP subnet it must configure a new and valid IP address, which requires a network layer handoff mechanism. This mobility across IP subnets is provided by Internet Engineering Task Force's (IETF) 'Mobile IP' protocol [72]. However, it is currently

unavailable to NEPWAK. If such a transition occurs NEPWAK enabled chair will be left, at least temporarily, stranded as a new connection is attempted.

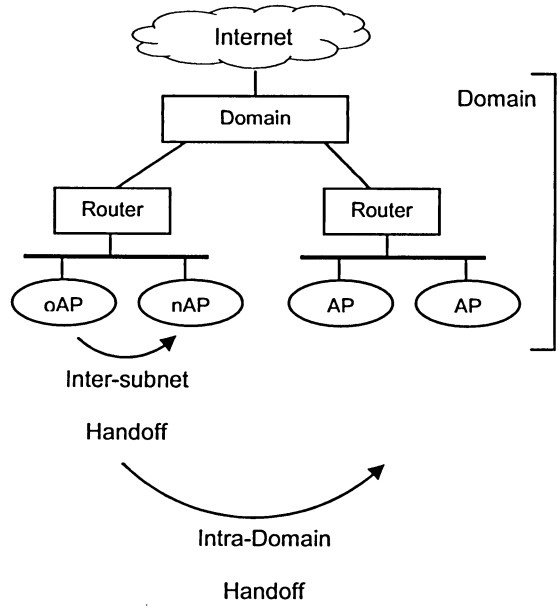

Figure 2.1: Inter-subnet and Inter-domain Handoff

In Mobile IP, to maintain network-level connectivity the handoff procedures are carried out at the network and lower layers at three participating entities, we call them, oldAP (oAP), newAP (nAP) and mobile node (MN – the wheelchair). The AP to which the MN had physical layer connectivity prior to the handoff is the oAP, while the AP to which the MN gets connectivity after the handoff is the nAP. Here, the wheelchair forms the MN. Mobile IP assigns two separate IP addresses to the MN, a Home Address and Care-of Address (CoA). The Home address is a permanent IP address on the MN's home network, and is used by higher layer protocols to identify the MN. The CoA, on the other hand, is a globally-routable IP

address assigned to the MN when it visits a foreign network and identifies its current point of attachment.

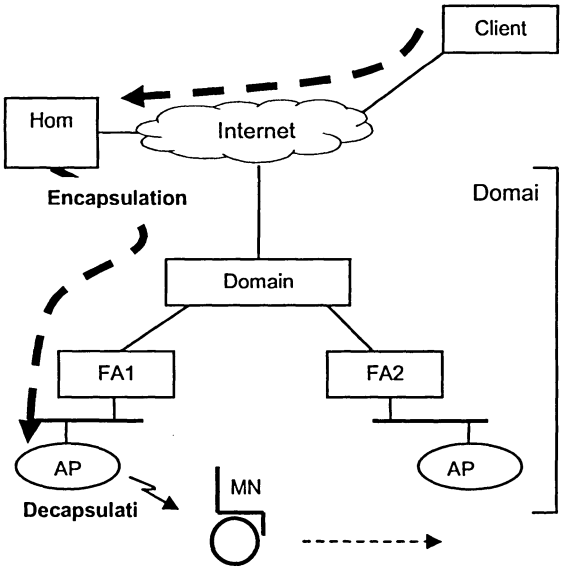

Figure 2.2: Mobile IP

The Mobile IP scenario (Figure 2.2) consists of two main entities – *Home Agent (HA)* and a *Foreign Agent (FA)*. When a MN moves to a Foreign Network, it discovers the FA through its MAC scan function [73]. The address of the FA sending out advertisements is heard by MN and is used as its CoA. The MN then registers this CoA with the HA. On receiving the registration request, the HA forms a binding between MN's home address and its CoA by modifying its routing table appropriately. When a client sends an IP packet to the MN's home address, it is intercepted by the HA and redirected to the MN's CoA. The redirection of IP packets is called *tunnelling* and is achieved by encapsulating the intercepted IP

packet in another IP header (*encapsulation*) having CoA as the destination address. The FA receives the encapsulated packet, extracts the original packet (*decapsulation*) and sends it to the MN.

Mobile IP is effective for mostly sedentary laptop users who do not cause frequent handoffs. The coverage area of an 802.11 AP at full rate is typically 100-300 m in diameter, a mobile robotic system like our NEPWAK moving at a speed of about 3 m/s may likely cause frequent handoffs between APs. Each time a handoff occurs, the MN goes through a time consuming registration process that disrupts its communication with the client. The network will drop packets destined to the MN during this period.

Therefore there is a need to address two main problems with Mobile IP:

1. Reducing the Registration delay.
2. Avoiding packet loss during handoff.

These problems have been widely researched [74, 75] and one interesting solution is called the fast-handover [76] technique.

Our investigation into the IP Mobility was with the aim to better understand the network behaviour during wheelchair's mobility. Implementing any IP Mobility protocols is beyond the scope of this thesis. We have however conducted some simulations using Mobile IP which will be presented in chapter 4.

Chapter 3 NEPWAK Architecture and Operation

In this chapter we will present the "Network Enabled Powered Wheelchair Adapter Kit's" (NEPWAK) detailed hardware and software architecture. We will discuss our novel human tracking and following system followed by Graphical User Interface design for handheld clients. This chapter has been divided into the following sections:

3.1 – Requirements Specification

3.2 – Conceptual System

3.3 – Detailed Hardware Architecture

3.4 – Detailed Software Architecture

3.5 – Human Tracking and Following System

3.6 – Graphical User Interface

3.1 NEPWAK Requirements Specification

Prior to the actual design and development of any project, it is important to lay down the requirements specification that defines what the project is ultimately supposed to do. There are several kinds of requirements such as - Functional requirements, Hardware and Software requirements, User Interface requirements etc. In short, the requirements specifications are the objectives that **should** be met. Stress is laid on the word "should", because the requirements tend to

change through the course of any project. The changes to the requirements can occur due to many reasons including economic necessity, or to meet compressed time lines, or even due to an end users' feedback. In this section we will lay down the initial Functional, Hardware and Software requirements for NEPWAK.

3.1.1 Functional Requirements Specification

Overall, the functional requirements for NEPWAK can be stated as – "A kit that connects to commercially available electric wheelchairs to provide telebotic services such as Audio-Video streaming, remote control and data acquisition through Wi-Fi networks. The kit must also provide local autonomous services such as object avoidance and co-operative human tracking and following capabilities." These requirements are discussed in greater detail below:

- Network Connectivity: The Kit should provide network connectivity via Wi-Fi networks. It should also provide an Ethernet port for wired network connection for wheelchair testing and diagnostic purposes.
- Video Streaming - The kit should be able to acquire real-time video from a provided onboard digital video camera and stream it to a connected network client. The video should be optimally compressed before streaming for efficient bandwidth usage.
- Audio Streaming - It must provide a full duplex real-time audio link to a network PC or handheld client. The audio should at least be telephone quality

and should be optimally compressed before streaming for efficient bandwidth usage.

- Control - The remote client should be able to fully manoeuvre the wheelchair remotely through an intuitive user interface with at least the same resolution of control as available through the local joystick. In order to avoid 'mode confusions' [chapter 2] and accidents due to human errors in remote control, NEPWAK should provide hierarchy in the control system. The design should allow the wheelchair joystick to exercise the highest level of control that can override the remote control and the object avoidance system.
- Supported Clients - NEPWAK should support both workstation and handheld clients through TCP/IP socket connections. However, only one client should be connected at any one time. The clients should be authenticated prior to connection and the remote services allowed to the client should be determined during authentication.
- Human Tracking and Following - To ease patient transport, NEPWAK should provide Human tracking and following capabilities to handheld clients. NEPWAK should be able to follow a person using a normal walking pace of approximately 1.4 m/s. The remote client should be able to turn on and turn-off the following system as and when needed.
- Object Avoidance - NEPWAK must provide hard, real-time, reactive object avoidance capability through the use of onboard proximity sensors. It should

also provide avoidance to falling down depressions such as staircases or ditches.

- Graphical User Interface (GUI) - NEPWAK will be used by medical practitioners who will have little or no knowledge of the underlying technology. The GUI should therefore be designed to be simple and very intuitive for medical practitioners. The GUI should typically display the video, sensory data, connectivity status, touch-screen control interface (for handheld clients) and descriptive error state messages with an audible beep.
- Safety – Some of the functionality of NEPWAK could put humans in danger therefore NEPWAK is a safety critical system; it must provide features to ensure safety and reliability. Since NEPWAK will be controlled through Wi-Fi networks, the clients must have a mechanism to monitor the received signal strength (RSS) from the wheelchair's onboard Wi-Fi card in ad-hoc mode, or the RSS from the connected Access Point (AP) in the infrastructure mode of control. In addition, as previously discussed, NEPWAK will provide Object Avoidance and Control hierarchy safety features.

3.1.2 Hardware Requirement Specifications

The hardware requirement for NEPWAK consists of onboard computational hardware, sensors, a Wi-Fi network interface card, Wi-Fi external antenna, a pan-and-tilt video camera, microphone, speakers and a power supply module. The main computer should be as small as possible and should have no moving

parts (including the mass storage which must be implemented in solid state form) for physical robustness. It should have low power requirements since it will be powered from the wheelchair's battery, and should have minimal effect on the wheelchair's battery life.

The computer should have sufficient standard input/output ports to connect to onboard camera, audio devices and other peripherals. The computer that exhibits these characteristics most closely is a PC104 single board computer (SBC). However, a computer with such high-level capabilities will not be able to provide low-level functionalities such as interfacing with sensors for object avoidance and controlling the wheelchairs motors. In order to handle these low level hard real-time functions, separate dedicated microcontroller based modules will be required that will communicate with the main computer through a standard protocol. The modules are discussed below:

- Wheelchair control module: It will be a microcontroller based custom interface board between the main computer and the wheelchair's motor driver. The module will take inputs from the wheelchair's local joystick and NEPWAK's main computer and will output motion commands to the wheelchair's motor driver. The module should be transparent to the wheelchair's local joystick and will provide local joystick override to remote control through the main computer – i.e. implements control hierarchy as discussed earlier.

- Input/Output module: It will be a microcontroller based custom board for interfacing wheelchair's peripheral sensors. The module will forward the sensory information to the main computer through a serial interface.

Sensors: NEPWAK will use proximity sensors to implement the obstacle avoidance system. The sensors will be strategically placed both in front and at the back of the wheelchair. Another sensor facing downwards will be use to monitor the surface just ahead of the wheelchair to avoid falling down the stairs or into a ditch.

Audio & Video hardware: NEPWAK will make use of a commercially available USB/Firewire Pan-and-Tilt video camera for providing video feedback. For audio, NEPWAK will use a commercially available microphone and speakers.

Power Supply: NEPWAK will be powered through the wheelchair's lead-acid batteries. An efficient DC-DC converter should be used to provide the required voltage-current to the kit.

3.1.3 Software Requirement Specifications

The operating system must support all the computer peripherals discussed above. It should support multitasking, real time multithreading and TCP/IP networking – the essential components for developing multimedia streaming

applications. It should provide and support an application programming interface (API) for audio and video acquisition and compression, TCP/IP sockets, and serial and parallel IO. An embedded server application for NEPWAK's single board computer, and workstation as well as handheld client applications will be developed to meet the functional requirement specifications discussed earlier.

3.2 NEPWAK Conceptual System

NEPWAK relies on existing wheelchair technology components and is intended to retrofit existing differential drive wheelchairs to provide telebotic services. The wheelchair is equipped with a Single Board Computer (SBC), a pan-and-tilt USB video camera, microphone, speakers, peripheral IR sensors and a PCI WiLan network card with an external antenna (Figure 3.1).

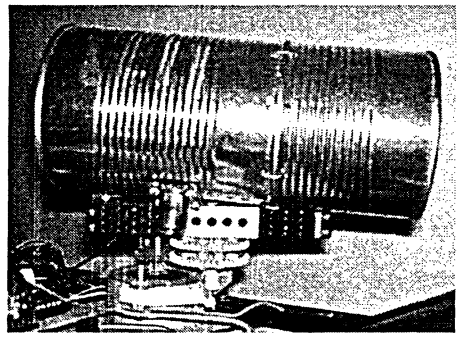

Figure 3.1: NEPWAK's custom directional steerable antenna

Two microcontroller modules communicate serially with the SBC for sensor data acquisition and motion control respectively. One microcontroller-based custom circuit forms an interface between the SBC and the chair's motor control circuit. It is responsible for the wheelchair's motion control. Another microcontroller-based system is responsible for peripheral sensor data acquisition for object avoidance and provides support for the person tracking and following system. All electronics are powered using the existing wheelchair's batteries through an efficient DC-DC converter.

The SBC runs a custom server application that allows both Workstation and Handheld clients to connect in either infrastructure or ad-hoc mode. Essentially, it transforms the electric wheelchair into a mobile embedded server on the Wi-Fi network. The clients receive audio, video and other sensory feeds from the wheelchair. Through a Graphical User Interface the remote operator is able to maneuver the wheelchair or pan-and-tilt the onboard camera to inspect the surroundings or the wheelchair's occupant. Each client--whether PC or PDA--is identified by a unique ID that is maintained by a database on the server. The database also relates each client ID with its associated Service Set Identification (SSID), its priority for control. The server refers to the database for authentication during connection establishment and uses it to decide the services allowed to the client. A typical entry into this database is shown in table 3.1 below:

Index	SSID	PSWD.	Video	Audio	Ctrl.	Object Avoidance	Follow	Priority
1	Wheel1	PPC_Client	Yes	Yes	Yes	Yes	No	3

Table 3.1: Server Database for client authentication and service allocation

Here, the client 'PPC_Client' is allowed Audio, Video, Remote Control and Object Avoidance services, while the Human Following service is not allowed. The entries in this database can be modified or added by an administrator by logging into the server remotely through the Windows XP's Terminal Service Client.

In addition to telebotic services, NEPWAK also implements certain low-level autonomous intelligent behaviors such as obstacle avoidance and the higher-level behavior of human tracking and following. NEPWAK's object avoidance system uses proximity sensors strategically placed both in front and at the back of the wheelchair. Another sensor facing downwards will be used to monitor the surface just ahead of the wheelchair to avoid falling down the stairs or into a ditch. NEPWAK's novel human tracking and following system allows the wheelchair to track and follow a care provider carrying a Wi-Fi enabled handheld computing device, thus potentially easing patient transportation in venues such as extended care facilities. The NEPWAK's modular architecture also allows connecting medical sensors such as pulse-rate monitors or temperature sensors for medical telemetry [although this is beyond the scope of this thesis]. NEPWAK

therefore transforms a mundane electric wheelchair into a mobile medical telecommunication platform suited for remote control, monitoring and care.

3.3 Detailed Hardware Architecture

The following block diagram represents NEPWAK's actual hardware architecture:

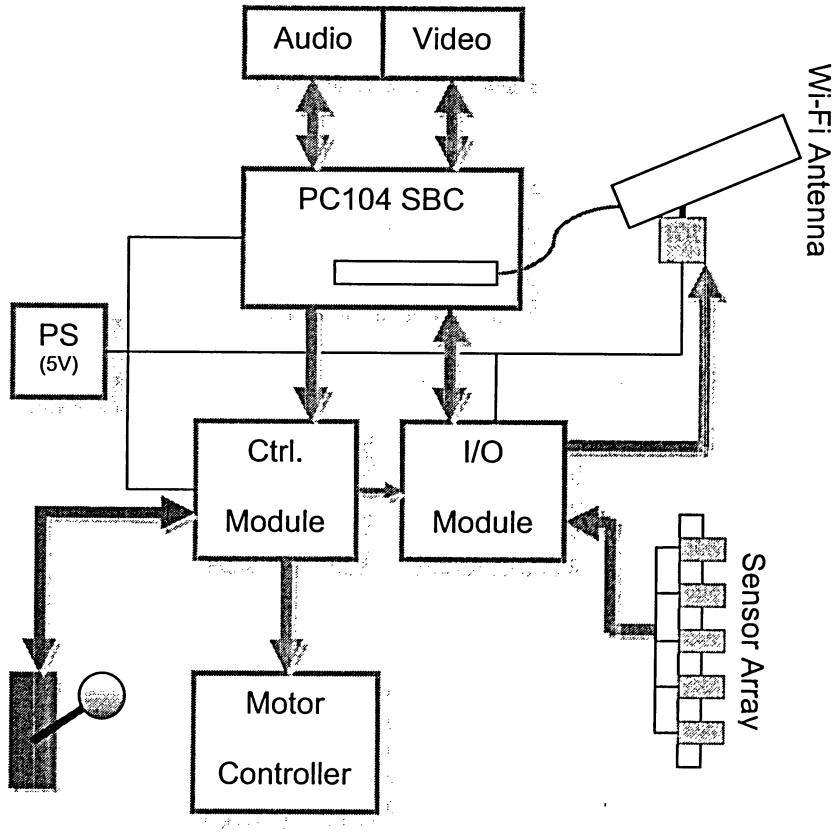

Figure 3.2: Detailed Hardware Architecture

Referring to the hardware block diagram above, the motor controller and the local joystick are not a part of the NEPWAK. They are the existing wheelchair components that directly connect to NEPWAK. NEPWAK's package contents, if commercialized, would include the following:

1. PC104 Single Board Computer (SBC)
2. PCI Wi-Fi network interface card
3. Control Module
4. Input/Output Module
5. DC-DC converter

Within a single enclosure

6. Sensor array
7. USB Pan-n-Tilt video camera
8. Head phone with microphone
9. Steerable Wi-Fi external antenna
10. Cables and connectors
11. Server and client software

3.3.1 PC104 Single Board Computer

Electric wheelchairs have a very limited space onboard and it is not sufficient enough to accommodate a standard PC/AT motherboard or even a laptop computer. While the PC and PC/AT architectures have become extremely popular in both general purpose (desktop) and dedicated (non-desktop)

applications, their use in embedded microcomputer applications has been limited due to the large size of standard PC and PC/AT motherboards and expansion cards. However, the needs of embedded applications have been satisfied by employing the similarly architected PC104 board, with the following key differences:

- A reduced form-factor, of 3.550 by 3.775 inches (90 by 96 mm).
- The elimination of the need for backplanes or card cages, through its self-stacking bus.
- Minimization of component count and power consumption (to typically 1-2 Watts per module), by reducing the required bus drive current on most signals to 4 mA.

PC/104 (or PC104) is an embedded computer standard by the PC/104 Consortium that defines both a form factor and computer bus. Unlike the popular ATX form factor, PC/104 is intended for specialized uses, such as for a data acquisition, robotics or industrial control system. This form factor has no backplane; instead components come in modules that are stacked one atop another.

Their small form factor and low power consumption makes them an ideal platform for robotic applications. NEPWAK uses the PCM-9575, a PC104-Plus module with low power VIA Eden 600MHz CPU with LAN, VGA/LCD and Audio. This

PC104 module forms the main NEPWAK computer providing high-level functionality of network connectivity, audio-video acquisition, compression and streaming, as well as controlling the Input/Output and the Control modules through serial communications. The specifications of PCM-9575 PC104 board are stated in Appendix A.

3.3.2 Input/Output Module

NEPWAK's Input/Output module is a MC68HC11 microcontroller-based system that interfaces distance sensors, controls the Wi-Fi steerable antenna and provides serial, parallel and analog-to-digital ports for future expansion. We use the MPP 68HC11 module (Figure 3.3) developed in Ryerson University's Electrical Engineering Department [77].

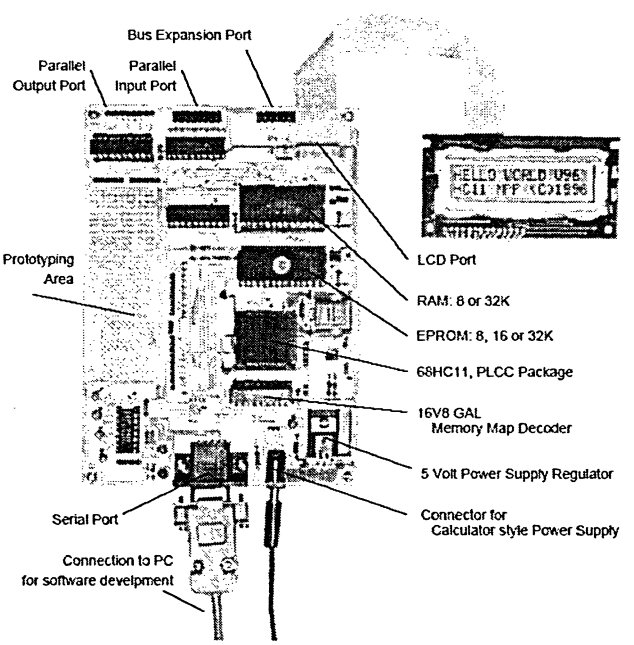

Figure 3.3: Input/Output Module using MPP 68HC11 board

The MPP 68HC11 module is very suitable for our purpose as it provides us the following features:

- Serial Communications Interface (SCI): This is used to communicate with the PC104 SBC at a baud rate of 4800 bytes/sec.
- General purpose parallel IO port: This is used to control the Wi-Fi steerable antenna.
- 8 Channel, 8 bit resolution analog to digital converter (ADC): This is used to interface the Infrared proximity sensors on NEPWAK.
- 32 Kbytes EEPROM and 32 Kbytes RAM: Sufficiently large memory is available to support large binary machine-code generated through C Cross-compilers.
- Monochrome LCD display: This is used to display local NEPWAK status - such as network connectivity, current state, error states, battery life etc.

3.3.3 Control Module

In a typical electric wheelchair a local joystick connects directly to the wheelchair's motor controller. In a NEPWAK retrofitted electric wheelchair, however, there is a control module (Figure 3.4) that interfaces the onboard PC104 Single Board Computer to the motor controller. This control module also transparently interfaces the local joystick to the motor controller and provides local joystick override to remote control. The control module therefore emulates the wheelchair's joystick. In order for us to develop the control module we had to

reverse engineer the onboard joystick to understand its electrical characteristics. This was done by probing the joystick connections through an oscilloscope.

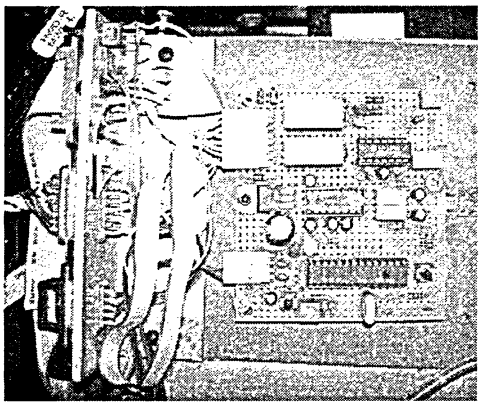

Figure 3.4: Control Module using PIC16F876 microcontroller

Electric wheelchairs use analog joysticks. In order to communicate a full range of motion to the computer, a joystick needs to measure the stick's position on two axes -- the X-axis (left to right) and the Y-axis (up and down). We observed that depending on the joystick position the voltage varies between 3.3V to 8.5V with 5.9V being the voltage at rest, in both X and Y directions (Figure 3.5).

In order to emulate these voltages, the control module uses a PIC microcontroller (PIC16F876) [Appendix B] board. The control module reads the binary X and Y values from the PC104 SBC using its built-in Universal Serial Asynchronous Receiver Transmitter (USART). It then creates two Pulse Width Modulated (PWM) signals with duty cycle based on the X and Y values, using the PIC's

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dedicated PWM generator. This signal is then conditioned through an Operation Amplifier (Op-Amp) to produce the correct DC offset and then sent to the wheelchair's motor controller. The control module also monitors the local joystick through its Analog to Digital Converters (ADC) to allow local joystick override over remote control.

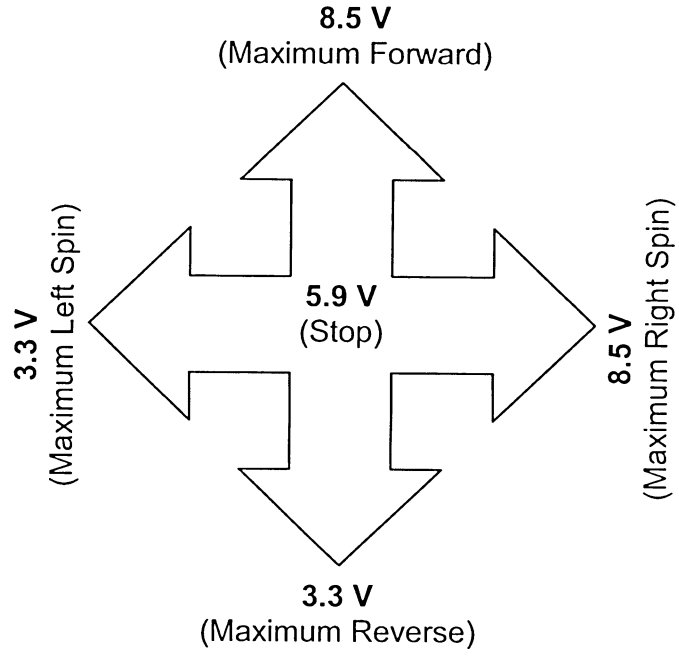


Figure 3.5: Wheelchair speed control voltages

3.3.4 DC-DC Converter

One of the very important design considerations in any battery operated mobile robot is the power supply. Studies on 'Driving Characteristics of Electric Wheelchair Users' [78] have shown that an average wheelchairs user drives for 8 Kms a day with a mixture of indoor and outdoor driving. A well-conditioned battery, under good conditions (flat surface, moderate ambient temperature)

provides an average of 24 Kms distance without re-charge. This implies that an average user requires re-charging every 3 days. Since, NEPWAK retrofitted wheelchairs use the wheelchair batteries for power; we wanted to have a minimal affect on the average battery life of the wheelchair.

Many electric wheelchairs have two 12 V, 30 Ah lead-acid batteries. NEPWAK components require only 5 V, 3.5 A (max) supply. A DC-DC conversion was therefore required. A common technique is to use linear voltage regulators integrated circuits (IC) such as L7812CV, which typically cost less than a dollar. These however suffer from poor efficiency, achieving a maximum of only 68%. In contrast, the switching regulators are an expensive option ($30 or more), but provide very high efficiency of approximately 80% or above.

	Linear	Switching
Efficiency	**Low to medium,** but actual battery life depends on load current and battery voltage over time; **high** if V_{IN}-V_{OUT} difference is small.	**High,** except at very low load currents (μA), where switch-mode quiescent current is usually higher.
Waste Heat	**High** if average load and/or input/output voltage difference are high	**Low** as components usually run cool for power levels below 10W
Size	**Small to medium** in portable designs, but may be larger if heat sinking is needed	Larger than linear at low power, but smaller at power levels for which linear requires a heat sink.
Total Cost	**Low**	**Medium to high** largely due to external components
Ripple/Noise	**Low**; no ripple, low noise; better noise rejection.	**Medium to high** due to ripple at switching rate

Table 3.2: Comparison Between Linear and Switch-Mode Regulators

For NEPWAK, we used a Lambda PM302-4S DC-DC switching regulator (Figure 3.6) with 81% efficiency and remote On/Off capability i.e. logic 1 at On/Off pin enables the unit and logic 0 disables it. The remote On/Off feature provides remote shutdown capability to NEWPAK.

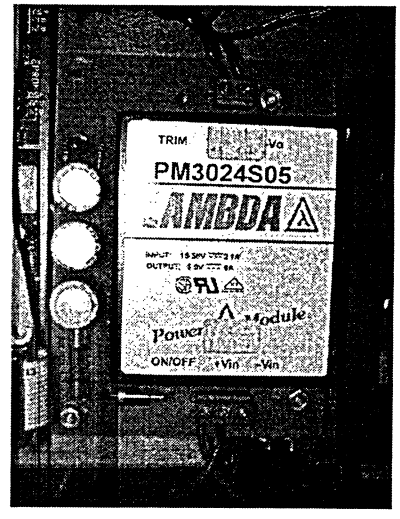


Figure 3.6: Lambda DC-DC converter unit on NEPWAK

3.3.5 Sensor Array

For obstacle avoidance, NEPWAK uses five infrared proximity sensors. A diagram showing the placement of sensors is presented in figure 3.7. The sensors connect to the Analog-to-Digital port of the Input/Output module.

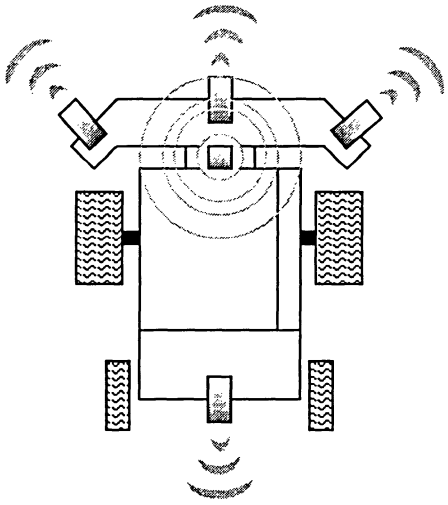


Figure 3.7: Placement of proximity sensors (bottom of chair view)

The proximity sensors that were chosen are the Sharp GP2D12 [Appendix C] general purpose infrared distance-measuring sensors. The Sharp GP2D12 infrared sensor is a compact, self-contained infrared ranging system that incorporates an infrared transmitter, receiver, optics, filters, detections and amplification circuitry [79] (Figure 3.8).

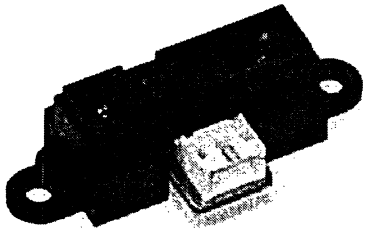


Figure 3.8: Sharp GP2D12 General Purpose Proximity Sensors

Other features that make it very suitable for NEPWAK are:

- Compact in size and low power consumption.
- Provides an analog output signal that connects directly to NEPWAK's Input/Output module.
- Uses a modulated infrared beam, so is highly immune to ambient light.
- Narrow field of view making it easier to obtain the range on a specific target.

3.3.6 USB Pan-n-Tilt Digital Camera

During the trials of our first prototype (discussed further in chapter 4), one of the pressing problems faced by the remote drivers was the extremely limited visual field available from the video camera. We had purposely aimed the camera forward and down after we discovered that the remote drivers complained of a loss of context if they could not see a component of the chair in the video image.

Unfortunately when the camera was repositioned the driver could only see approximately two meters in front of the chair. While this proves adequate for avoiding collisions it does not provide enough context for navigational purposes. In other words, if our drivers had not known the floor plan well they would have been unable to find their way through the building. Another aspect of the visual field problem is related to interacting with physical objects on either side of the chair. Since the driver could not see these components of the environment, we

observed many collisions that went unnoticed by the remote driver and were disturbing for the chair's occupant.

Learning from user feedback, we have incorporated a video camera with pan and tilt capability. The remote user is now able to turn and tilt the camera remotely to better observe and interact with the environment. The pan-n-tilt camera that we use is the Logitech's QuckCam Orbit; it provides 189 degree of pan and 102 degree of tilt (Figure 3.9).

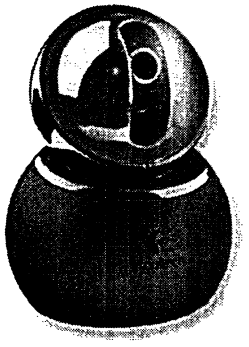


Figure 3.9: Logitech Orbit, NEPWAK's Pan-n-Tilt camera

3.3.7 Steerable Wi-Fi External Antenna

We have provided NEPWAK with a novel human tracking and following system to ease the cognitive load of both a remote driver and the chair's occupant while in transport. The system relies on two tracking techniques – a Wi-Fi-based and an Image Processing-based technique. The pose data from these systems are fused together in real-time to result in a robust and reliable tracking system.

In our Wi-Fi approach we use 802.11b Wi-Fi enabled PDAs as beacons. A custom-built highly directional and steerable antenna on the wheelchair scans the received signal strength (RSS) from the connected PDA. RSS values are sampled at every 3.6° during each scan covering 115 degrees. Roughly, the angle at which peak RSS value occur provides directional information while the magnitude of the peak signal strength itself provides a measure of the distance from the PDA. The steerable antenna is custom-made and is mounted on a stepper motor that is controlled through the Input/Output Module. The construction and principle of working of the antenna is discussed in section 3.5.

3.3.8 Other Components

Other hardware parts on NEPWAK are off the shelf components such as:

- PCI Wi-Fi network access card: We use the SMC 802.11b/g PCI Wi-Fi network access card.
- Headphone with Microphone for full-duplex audio.

3.4 Detailed Software Architecture

In this section we will present the detailed software architecture of NEPWAK's server software within the context of the Windows XP Embedded operating system as well as the .NET framework used for NEPWAK's software development. This section is broadly divided into the following subsections:

3.4.1 – Operating System – Windows XP Embedded

3.4.2 – Programming Platform - .NET

3.4.3 – NEPWAK Server Application

3.4.1 Operating System – Windows XP Embedded

NEPWAK's PC104 SBC runs the Windows XP Embedded (XPe) operating system. Windows XP Embedded is the componentized version of Microsoft Windows XP Professional. XPe is based on the same binary code as XP Professional, but XPe is marketed to developers of Original Equipment Manufacturers (OEMs), Independent Software Vendors (ISVs) and Independent Hardware Vendors (IHVs) that want the full Win32 API support of Windows but without the overhead of Professional. It runs existing off-the-shelf Windows applications and device drivers on devices with 32MB of Compact Flash memory, 32MB RAM and x86 architecture based microprocessor. The devices targeted for XPe have included ATMs, slot machines, cash registers, arcade machines, industrial robots, thin clients, set top boxes, network area storage, time clocks, and many other devices. Custom versions of the OS can be deployed onto anything but a full-fledged PC.

XPe is an ideal operating system for small footprint devices such as PC104 Single Board Computers. Since it is componentized, only individual OS components required can be included, thus reducing the overall size of the

operating system. Other factors that make it very suitable for our purposes are listed below:

- Extensive multimedia support including DirectX.
- Supports Windows Management Instrumentation (WMI) that is used for making Received Signal Strength Measurements (RSS) for Wi-Fi network cards.
- Supports all PC IO ports – COM, LPT, USB etc.
- Support for a wide variety of industry-standard networking technologies.
- Multiple boot options – such as Ethernet remote boot, Compact Flash, IDE etc.
- Efficient power management.

The custom image for Windows XP embedded for NEPWAK is 212 MBs in size and runs from a 256 MB compact flash on the PC104 SBC.

3.4.2 Programming Platform – .NET

The last few years have seen a proliferation of handheld and smart devices, and tremendous new applications have arisen. With the growth of handheld device usage in everyday life, there was a need for single powerful development platform to ease the application development and shorten the time to market new ideas. Microsoft's .NET platform offers a compelling and powerful software development platform. This single platform not only supports a wide range of

programming languages, but also supports development for both PC and smart devices such as pocketPCs.

The core of .NET is the .NET Framework, and at the heart of the .NET Framework is the Common Language Runtime (CLR). Under .NET, source code is not compiled directly to machine code, but instead to an intermediate language commonly referred to as IL. It is the CLR that activates objects, performs security checks, verifies type safety and allocates memory. It also manages memory through an extremely efficient garbage collector. Code written for the CLR is referred to as 'managed' code.

The .NET Framework provides one of the largest class libraries ever built, containing more than 5,000 classes. These are divided into a coherent set of over 90 namespaces. Third parties can add their own namespaces, as for example, NEPWAK uses the DirectX namespace to invoke DirectSound classes for audio capturing. We have implemented our own 'Object Tracking' class in C++ .NET and use it in our application written in VB .NET. Other features that make it a suitable choice for our usage are:

- Multi-threading with 256 thread priorities.
- Thread time slices can be varied – per thread quantum
- Image acquisition and compression support.
- Windows TCP/IP socket support.

- Windows Measurement and Instrumentation libraries.

3.4.3 NEPWAK Server Application

The server application is the single most complex part of the NEPWAK project. The server is a multi-threaded application written in C++ .NET and is responsible for all NEPWAK operations and services.

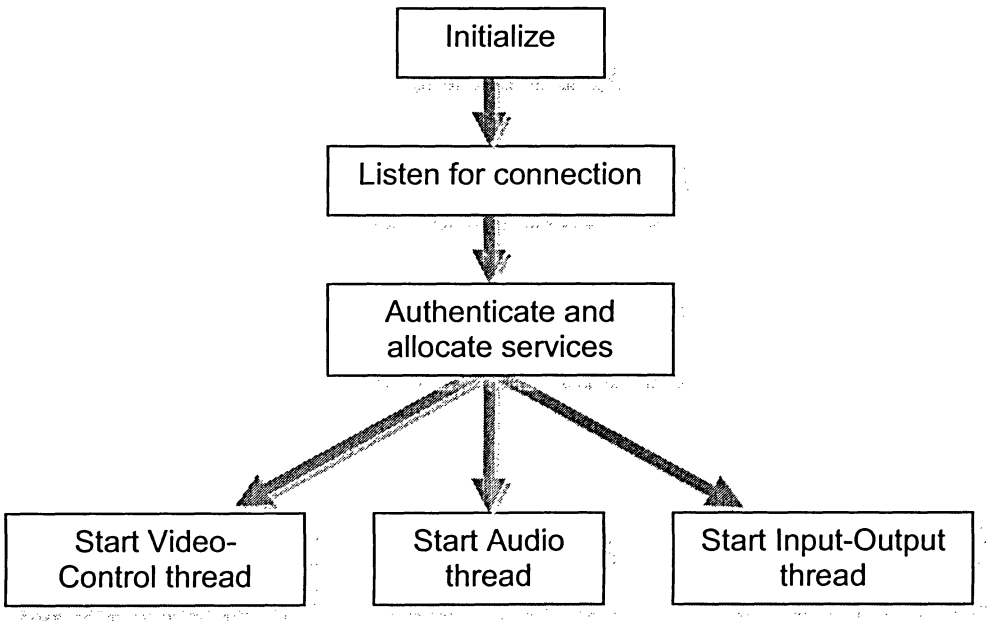


Figure 3.10: Server Application Flowchart

The server makes use of Microsoft's DirectX library [80] for multimedia and control, it also employs Windows' Measurements and Instrumentation [81] libraries for Wi-Fi signal strength measurements. The server communicates with the Input/Output Module and the Control Module through a serial port and

connects to the remote client through TCP/IP sockets over Wi-Fi networks. Above, we have described the server application through the use of a flowchart in figure 3.10. Figure 3.11a and 3.11b, depicts the flowcharts for the video-control thread and Input-Output thread of the server application respectively.

The server application automatically runs when the PC104 SBC boots into Windows XP Embedded. It then connects to an available Wi-Fi network in infrastructure mode, initializes the Input/Output and Control modules and starts listening for TCP/IP socket connection requests from remote clients. At this point, it also starts informing the Input/Output module of its status at regular intervals.

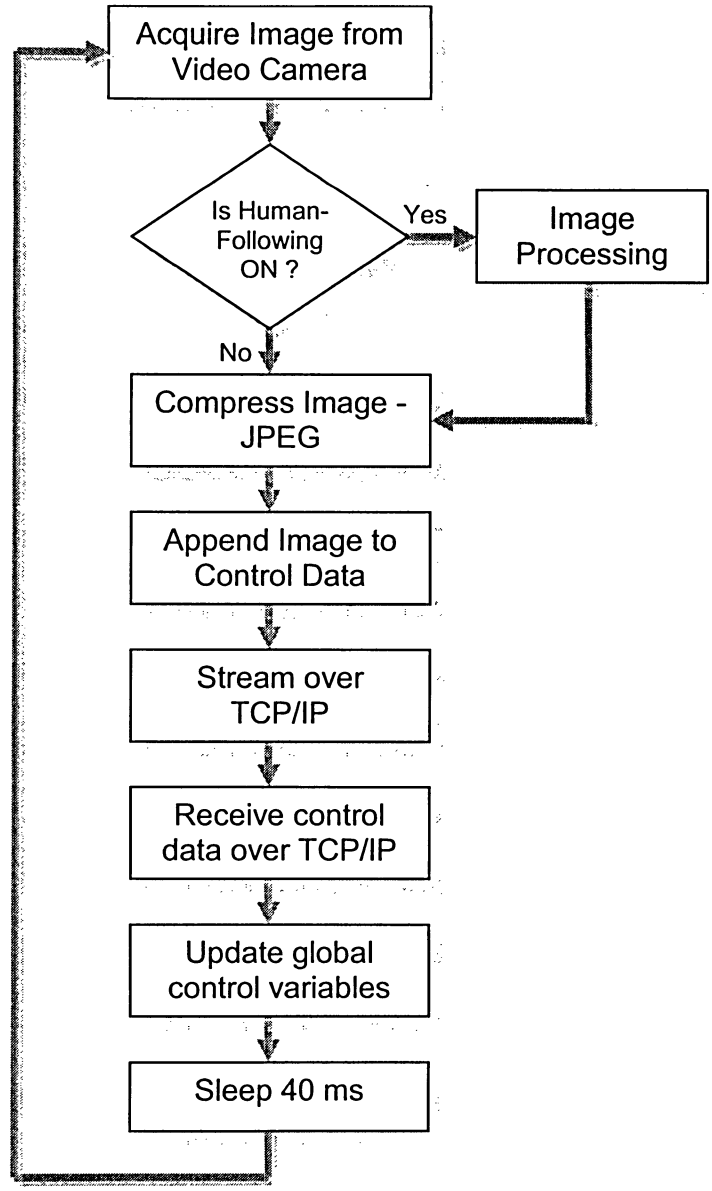


Figure 3.11a: Video-Control thread

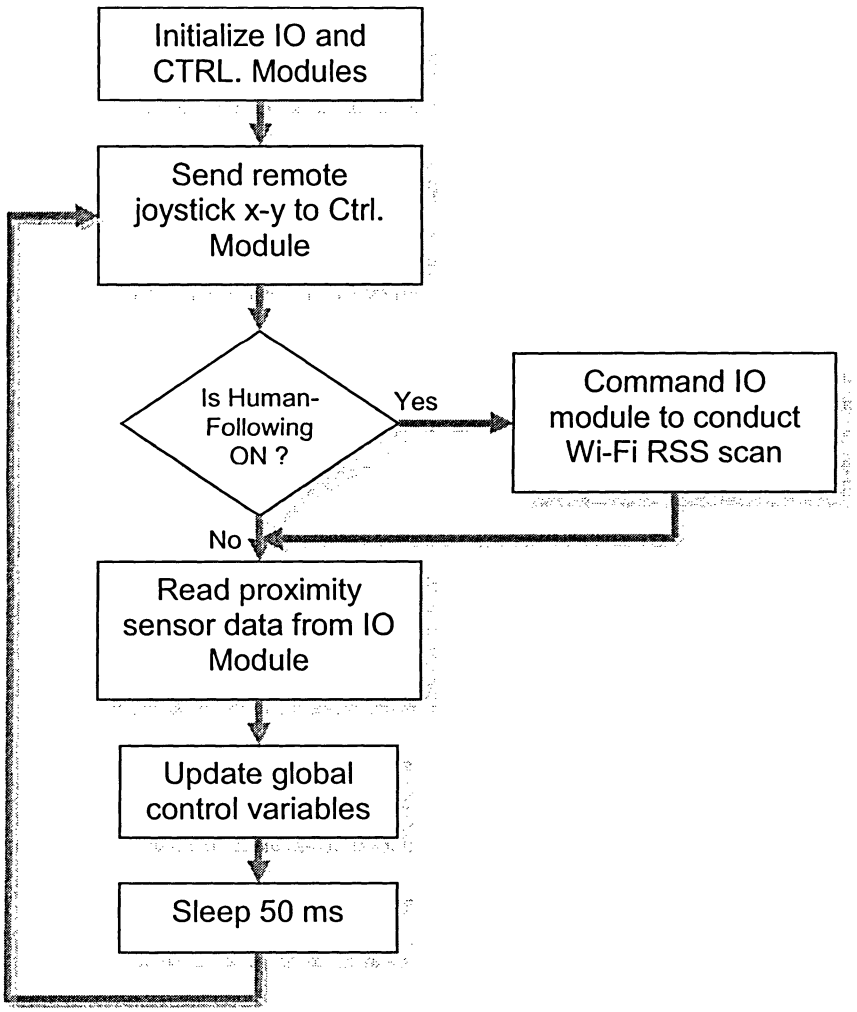


Figure 3.11b: Input-Output thread

When the server receives a connection request, it first authenticates the client and also determines the services allowed for that client. Each client, whether PC or PDA, is identified by a unique id which is maintained by a database on the server. The database also relates each client id with its associated Service Set

Identification (SSID), mode (infrastructure or ad-hoc) and its priority for control. The server refers to the database for authentication during connection establishment and uses it to decide the services – audio, video, control, human-following etc. allowed to the client. It then starts the video-control, IO and the audio threads. The video-control and IO threads communicate with each other through shared variables.

The Video and Control functions are embedded in a single thread that runs with the highest priority and maximum quantum [82]. This thread basically acquires a raw bitmap image from the video camera and compresses it to JPEG format using the .NET bitmap library. The compressed image is saved into the main memory as a memory stream [83]. This memory stream is them appended to 10 bytes of custom header (Figure 3.12) that contains the following control information – proximity sensor data, error codes, human-following status, Wi-Fi signal strength, image frame number, image file length. The header format is described in table 3.3 below. The complete frame is then transmitted to a remote client over a TCP/IP socket. We embed the image data with the control feedback information for more efficient network usage.

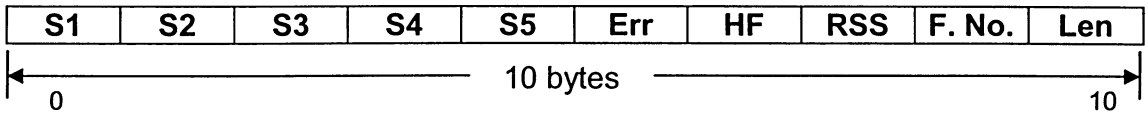


Figure 3.12: Video-Control Header

Data	Size (bits)	Description
S1 to S5	40	S1 to S5 are the proximity sensor array values acquired from the Input/Output Module. 1 byte each.
Err	8	Error Code to inform remote operator of any errors. Default value is 0 i.e. no errors.
HF	1	Human Following flag. It is set to 1 when the human following request by the remote operator and is accepted by the server. Default value is 0 i.e. human following is Off.
RSS	8	Wi-Fi received signal strength received by the server. Remote control is active only when RSS > 60
F. No	8	Image Frame number. It is set to 0 after every 255 frames.
Len	16	Total frame length in bytes not including the header.

Table 3.3: Video Control Header

Thereafter, the server receives 7 bytes of control information (Figure 3.13) from the remote client. The control information includes remote joystick data, human-following status, disconnect request, restart request, and human tracking data such as aspect ratio and color ratio discussed later in the chapter. The control information is described in table 3.4. This completes the thread cycle. It repeats after every 40 ms.

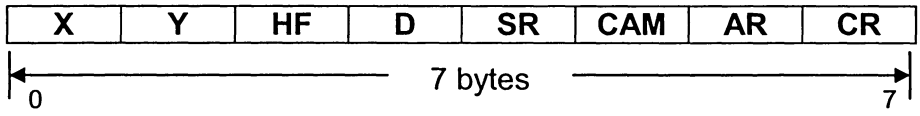


Figure 3.13: Control Information from remote client

Data	Size (Bits)	Description
X	16	Remote joystick X coordinate. Value varies between 0 and 900, 450 is the default rest position.
Y	16	Remote joystick X coordinate. Value varies between 0 and 900, 450 is the default rest position.
HF	1	HF request flag. Set to 1 when the remote operator requests for human following.
D	1	Disconnect request flag. Set to 1 when the remote operator sends a disconnect request.

SR	2	Remote Shutdown/Restart request. Remote operator can remotely shutdown or restart the server by using this field. **00** = NOP; No Operation **01** = Shutdown **10** = Restart
CAM	4	These bits are used for remotely moving the pan-n-tilt video camera. Only three bits are being used, the fourth MSB is to complete the byte length. **000** = NOP; No Operation **001** = Tilt Up **010** = Pan Right **011** = Tilt Down **100** = Pan Left **101** = Move to home position
AR	8	Aspect Ratio; this byte is used for human following purpose and is discussed later.
CR	8	Color Ratio; this byte is used for human following purpose and is discussed later.

Table 3.4: Control Information from remote client

The audio thread is only responsible for streaming and receiving audio. NEPWAK uses telephone quality audio, which is a low quality audio however a widely accepted standard. The overall quality of digitized sound is characterized by the Sampling rate and sample resolution. For digitized speech, sampling rates and sample resolutions typically range from low (telephone) quality values of 8000 Hz sampling rate with 8-bit samples to CD quality at a 44100 Hz sampling rate with 16-bit samples. With telephone quality audio (8000 Hz/8bit) NEPWAK requires 64 Kbps bandwidth for audio, which is generally available on 802.11b WiLANs supporting up to 11 Mbps.

For audio capture and playback we use the DirectSound class in Microsoft's DirectX library. DirectSound includes methods for recording and playing audio

with very low latency, and allows a high level of control over the sound pipeline. We use an audio frame size of 1024 bytes that corresponds to a 128 ms of audio. This induces a playback delay of 128 ms, which provides a sufficient jitter-buffer [84] on the client side to reproduce continuous smooth audio over WiLAN networks [44].

Lastly, the IO thread is responsible for communicating with the Input/Output and Control modules through the serial port. It sends the X-Y coordinates of the remote joystick to the control module for manoeuvring the wheelchair. It also communicates with the Input/Output module for sensor data acquisition and for repositioning the steerable Wi-Fi antenna for human tracking. The data frames exchanges between the IO thread and the Input/Output module software are depicted in figure 3.14.

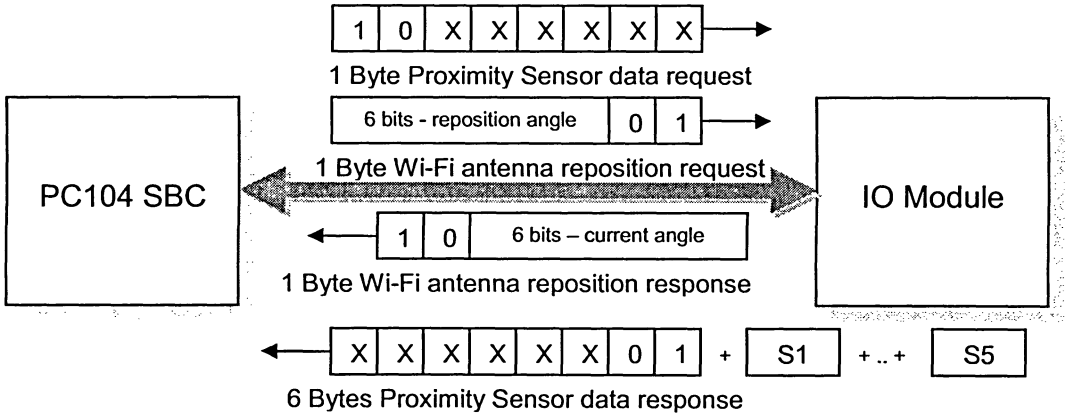


Figure 3.14: Data communication between the PC104 SBC and the Input/Output Module

3.5 Human Tracking and Following System

Patient transportation in health and extended care facilities has always been a problem and the problem is getting bigger [85, 86]. Physically challenged patients who cannot use a powered wheelchair have to be transported in manual wheelchairs requiring additional staff simply for moving chairs. The use of powered wheelchairs does not solve the problem as they do not have remote control capabilities. However, NEPWAK equipped wheelchairs could effectively address the problem. Medical staff carrying Wi-Fi enabled PDAs can form an ad-hoc connection with the wheelchair and can conveniently provide remote control and effective transport. Transporting patients over extended distances this way can be problematic for staff assigned this task. Controlling the wheelchair through the PDA's touch-screen Graphical User Interface (GUI) while walking alongside can also be difficult. It is here where NEPWAK's novel human tracking and following capability can provide semi-autonomous assistance to a care provider. NEPWAK will allow the wheelchair to follow the provider through corridors and within rooms—potentially greatly easing the task of transporting patients.

The NEPWAK human tracking system relies on the fusion of two separate tracking systems – a Wi-Fi based [87,88] technique and color-blob tracking through image processing, for robustness and greater reliability. Here, we will first discuss both the systems independently and then present our fusion

algorithm that combines the pose data from the two systems. The following mechanism and experimental results will be discussed in chapter 4.

3.5.1 Wi-Fi Based Human Tracking

Human tracking techniques employing active beacons [66, 67] (Infrared, Ultrasonic etc.) on the human body are a very simple approach, yet not widely supported. They are considered 'intrusive' since they require people to carry a dedicated beacon device. Their biggest advantage however, is that they greatly simplify target discrimination as each beacon can transmit a unique identifier signal. Our approach is similar except that the chair's occupant or the medical staffs carries a Wi-Fi enabled PDA instead of a dedicated beacon. We believe carrying a PDA is not intrusive and, in fact, is becoming more and more common. With the advent of Wi-Fi technology, PDAs are commonly used as mobile communication device, organizers and are extensively being used in medical settings [10, 11].

In our approach we use 802.11b Wi-Fi enabled PDAs as beacons. A custom-made highly directional and steerable antenna on the wheelchair scans the received signal strength (RSS) from the connected PDA. This RSS is a value that ranges between 0 and 100. The steerable antenna is mounted on a stepper-motor and is controlled through the Input/Output module (Figure 3.15). RSS values are sampled at every 3.6° during each scan covering 115 degrees.

Roughly, the angle at which the peak RSS value occurs provides directional information while the magnitude of the peak signal strength provides a measure of the distance from the PDA (Figure 3.15). The angle at which the peak RSS occurs is referred to as the 'Region of Interest' (ROI). With a resolution of 3.6° and a total scan angle of 115°, the Wi-Fi system can provide 32 possible ROIs. This ROI is then used by the image processing technique to confirm the target – human torso in this case. On successfully acquiring the target, the image processing technique calculates the distance of separation. The pose data from both the techniques is then fused to find the final location of the person being followed.

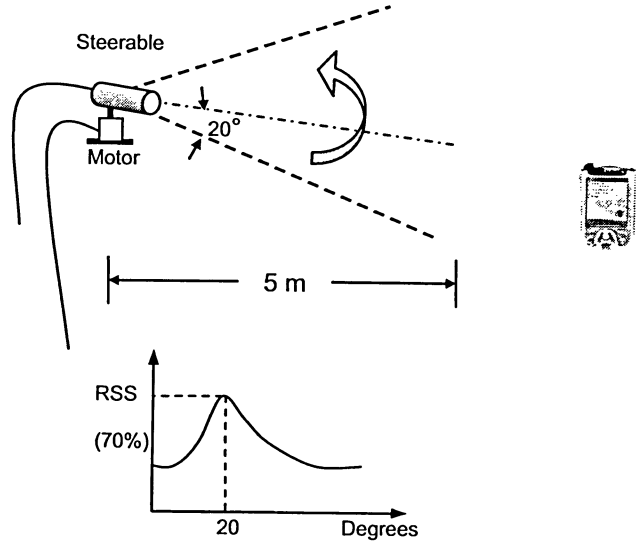


Figure 3.15: Steerable Wi-Fi Antenna

3.5.1.1 Wi-Fi Signal Propagation

The IEEE 802.11b standard uses radio frequencies in the 2.4GHz band, which allows license-free operation. Accurate prediction of signal strength is a complex task since the signal propagates by unpredictable means. Due to reflection, refraction, scattering and absorption of radio waves by structures inside a building, the transmitted signal most often reaches the receiver by more than one path; this phenomenon is called multipath fading. The signals from multiple paths combine and produce a distorted version of the transmitted signal. The received signal therefore varies with time and the relative position of the transmitter and the receiver. In order to locate the direction of the source (a PDA in our case) we constructed a steerable directional waveguide antenna [87,88] having a gain of 12dB. Being directional it transmits and receives the signal over a very narrow beam width. Hence, the received signal strength (RSS) achieves the peak when the antenna is directly pointing at the source PDA.

3.5.1.2 Waveguide Antenna Design

A waveguide is a material medium that confines and guides a propagating electromagnetic wave. In the 2.4 GHz frequency band, a waveguide normally consists of a hollow metallic conductor, usually rectangular, or circular in cross section similar to a tin can. A waveguide which is closed at one end acts like a short circuited coaxial cable. The incoming high frequency (hf) signal reflects

from the closed end and forms a standing wave inside the waveguide. The standing wave has maxima and minima points as shown in figure 3.16.

There are three different wavelengths in the waveguide. Here they are marked as Lo, Lc and Lg. Lo is the wavelength of the hf in open air [88].

$$\mathbf{Lo\ (mm) = 300 / f\ (GHz)} \qquad (3.1)$$

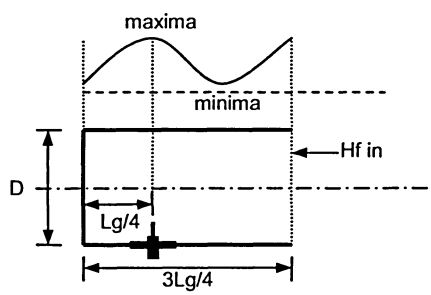


Figure 3.16: Waveguide antenna design

Lc is the wavelength of the low cutoff frequency which depends on the tube diameter (D).

$$\mathbf{Lc = 1706 \times D} \qquad (3.2)$$

Lg is standing wavelength inside the tube; it is a function of both Lo and Lc.

$$\mathbf{Lg = 1 / \sqrt{((1/Lo)^2 - (1/Lc)^2)}} \qquad (3.3)$$

It is important to note that the standing wavelength (Lg) is not the same as the wavelength of the hf signal in open air (Lo). Circular waveguides with large diameters act nearly as in the open air where Lg and Lo are almost the same. But when the waveguide's diameter becomes smaller the Lg increases effectively until it becomes infinite and the hf signal is not confined in the waveguide at all. In effect, the waveguide tube acts as a high pass filter which limits the wavelength Lc. Inverse values of Lo, Lc and Lg forms sides of a right angled triangle related through the Pythagoras equation as:

$$(1/Lo)^2 = (1/Lc)^2 + (1/Lg)^2$$

Hence,

$$Lg = 1 / \sqrt{((1/Lo)^2 - (1/Lc)^2)}$$

We made our waveguide antenna using readily available and expedient tin-cans having the diameter of 85 mm. Using equation (3.1), (3.2) and (3.3) we calculate Lg/4 to be 62 mm, this is the distance from the closed end where the first maximum point occurs.

3.5.2 Human Tracking through Image Processing

Our second approach on tracking is based on color-blob tracking through image processing and relies on the work presented in [89]. However, we have made many improvements to the generic color-blob technique to improve accuracy and reliability. The idea is to track a person's torso based on his/her coloured clothing

and torso's aspect-ratio. The technique involves two phases: A startup phase where a person wearing a uni-coloured shirt is identified by the system and then the tracking phase tracks the person based on the information recorded during the startup phase and the ROI provided by the Wi-Fi tracking system.

3.5.2.1 Start-up Phase

At startup, first, a person carrying a PDA forms an ad-hoc connection with the wheelchair so that he receives audio, video and other sensory feeds onto his PDA. He then selects the human following menu item that displays an empty rectangular area. Looking at the video feed, he positions himself in front of the onboard camera, so that his shirt completely occupies the rectangle, and then clicks the 'Follow Me' button. As a first step, the shirt is classified as Red (R), Blue (B) or Green (G) whichever forms the highest component of the uni-coloured shirt. Then, the normalized color component (NCC) of the shirt's colour is determined for each pixel in the rectangle using one of the equations below:

$$r' = \left[\frac{R}{R + G + B} \right] \qquad (3.4)$$

$$g' = \left[\frac{G}{R + G + B} \right] \qquad (3.5)$$

$$b' = \left[\frac{B}{R + G + B} \right] \qquad (3.6)$$

For instance, equation (3.4) would be used to find the normalized red component if a red coloured shirt were to be tracked. Next, the low and high thresholds (C_l, C_h) of the shirt's colour are determined. We determine the thresholds by computing the mean (μ) and the variance (σ) of the NCC values, then using the equations:

$$C'_l = \mu_c - \sigma_c \qquad (3.7)$$

$$C'_h = \mu_c + \sigma_c \qquad (3.8)$$

At the end of the startup phase $C'_{l/h}$ are known, where C could be R, G or B depending on the shirt's color. The Wi-Fi antenna also makes an initial scan during the start-up phase.

3.5.2.2 Tracking Phase

The tracking phase is further divided into 3 stages: Search, Acquisition and Lock, as described below in detail.

Search: We consider that the raw image acquired from the digital camera is made of 32 imaginary vertical regions that coincide with the 32 possible regions of interest (ROI) that the Wi-Fi system can provide. After a complete scan, when the Wi-Fi system provides a ROI. The image processing technique uses this ROI along with its two adjacent regions to search for ten vertically continuous pixels such that their NCC lies between C'_l and C'_h, we call them 'Target Pixels'. In simple terms, we are trying to search for pixels that belong to a person's uni-

coloured shirt in only the region of the image that the Wi-Fi system points to. That is, instead of searching the complete image and using valuable time and processing, we rely on the Wi-Fi system to provide us a ROI, and we focus our search in and closely around that region to improve our chances of finding the target to follow in a shorter amount of time. Also, one should note that by 'vertical continuous pixels' we **do not** mean the nearest vertical neighbours. A gap of two 'Spurious Pixels' is allowed within every pair of 'Target Pixels' and six such spurious pixels allowed among every ten target pixels. This will become clear with the following diagram.

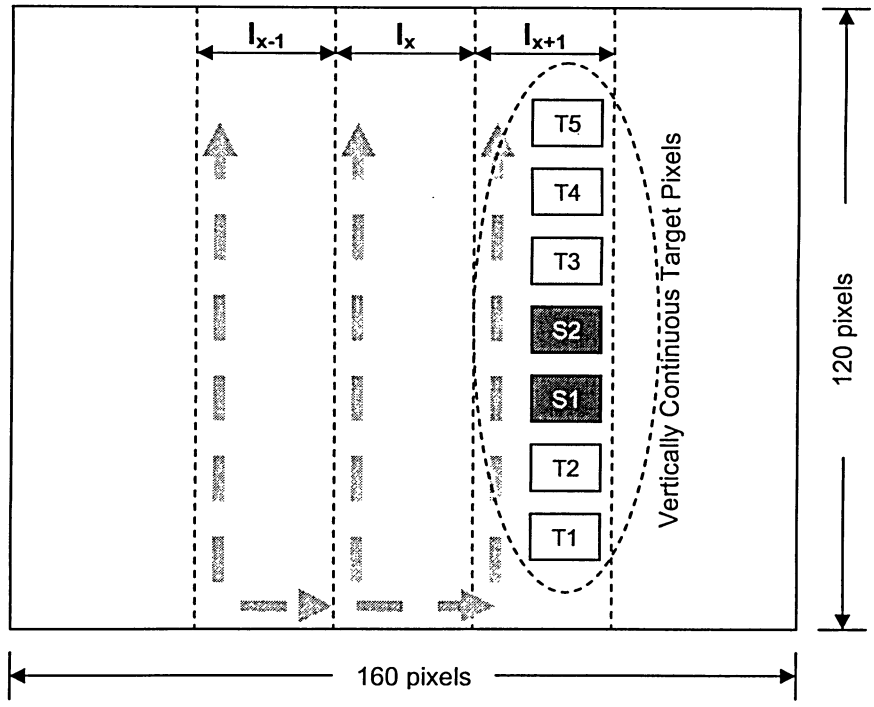


Figure 3.17: Search for Target Pixels

Examining the diagram above, let **I** be the complete image, and let $\mathbf{I_x}$ be the ROI provided by the Wi-Fi system. We will therefore search for ten vertical continuous target pixels in regions $\mathbf{I_{x-1}}$, $\mathbf{I_x}$ and $\mathbf{I_{x+1}}$ from left to right and bottom to top in each region. Let the pixels marked with $\mathbf{T_x}$ be the target pixels i.e. they conform to the rule:

$$C'_l < NCC_{Tx} < C'_h \qquad \text{(ix)}$$

Furthermore, let the pixel marked $\mathbf{S_x}$ be the spurious pixels. Then, pixels from $\mathbf{T_1}$ to $\mathbf{T_5}$ are considered vertical continuous target pixels. We allow two spurious pixels between a pair of target pixels to ignore the presence of camera noise, or shadows cast due to wrinkles on the shirt and similar spurious conditions. The presence of ten such vertical continuous pixels completes the search stage, and the next stage is to acquire the target.

Target Acquisition: Once the search stage is complete we are definitely in the region that contains a portion of the person's shirt. We then form a best fit rectangle around all the continuous target pixels in vertical and horizontal direction. An example of the best fit rectangle is shown in figure 3.18.

Now, as a heuristic, if the ratio of the height to the width of the rectangle (aspect ratio) is 1.8 ± 0.2, we consider that target is successfully acquired. The vertical centre of the rectangle provides the direction, while the height of the rectangle provides a measure of the distance. If on the other hand, the initial aspect ratio

does not lie within the acceptable range, the target is rejected and the process runs a complete search through the alternate regions of the image.

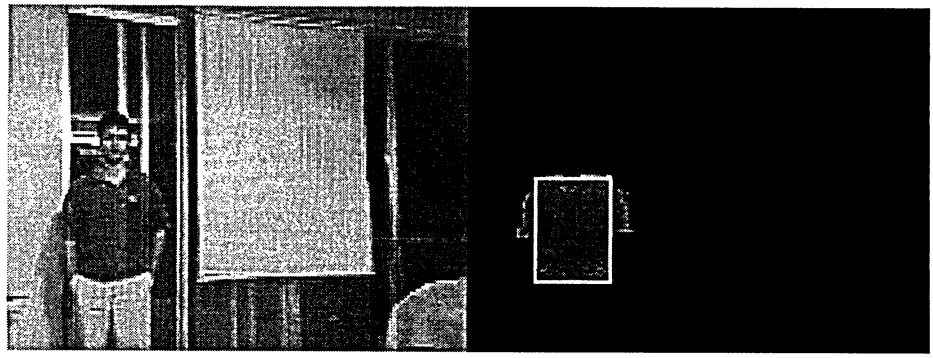


Figure 3.18: Best fit rectangle around all continuous target pixels

Target Lock: The Wi-Fi RSS scans take one second to complete, therefore the ROI is provided to the Image Processing system once every second. Image Processing system however is capable of processing ten image frames per second (fps). Therefore in the absence of a refreshed ROI, the system generates its own ROI. The generated ROI is the region occupying the centre of the target rectangle from the previous frame. This helps in very quick target acquisition and we call this 'target lock'. Once the Wi-Fi scan is complete the image processing system accepts the new ROI for its search.

At this point one might ask: *Why not always keep the centre of the target rectangle as the ROI for the next frame?*

The answer is, that in the case of intersecting targets. Consider two nurses wearing the same coloured uniforms and moving side by side where only one of them must be tracked and followed. In the case their path intersects, the image processing system will not be able to distinguish between the two nurses during the intersection. Once their paths separate the system might lock on to the wrong nurse. However, the Wi-Fi system will always point to the nurse carrying the connected PDA. Hence, even if the wrong target is acquired for a short period of time (less than one second), the ROI provided by the Wi-Fi system will provide the correct ROI after the scan is complete.

Through experiments we determined that even after successfully locking onto the target we were frequently loosing it. We realised that the target acquisition criterion based on the aspect ratio was very stringent. As the person turns sideways, the aspect ratio of the torso changes – height remains constant but the width decreases. This was resulting in target acquisition failure, and triggering complete image search. In order to solve this problem, we modified our target acquisition criterion. We implemented a system that in order to initially acquire the target the acquisition criterion be the same as before. However, after the target is acquired and locked, the aspect ratio requirement is relaxed to 2 ± 1, until the target is lost. This solved the problem of frequent target loss and re-acquisition.

3.5.3 Fusion of pose data

Distinguishing people wearing the same colored shirts is a formidable task through image processing. The Wi-Fi technique on the other hand does not provide an accurate separation distance. However, fusing the pose data from these separate systems can provide a highly accurate and robust tracking system.

A Wi-Fi scan can provide 32 (115/3.6) possible directions or ROIs. The color-based tracking on the other hand works on images of size 160 x 120 pixels and has a viewing angle of nearly 90 degrees. We consider that the raw image acquired from the digital camera, is made of 32 imaginary vertical regions. It can therefore also provide 32 different directions based on where the centre of the tracked color blob lies. In order to produce a match of the ROIs of the two systems, the steerable antenna and the video camera are placed along the same vertical plane on the wheelchair. The pose data generated by the two systems are then fused using the following algorithm to result is a robust and a very precise tracking system.

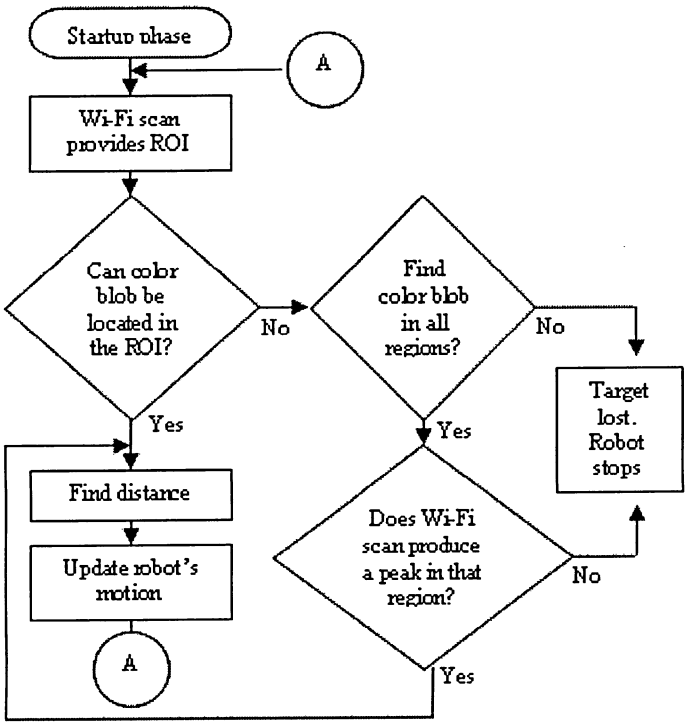


Figure 3.19: Pose data fusion

3.6 Graphical User Interface (GUI)

Developers often design for what they know, not what the users know. This age-old problem occurs in many other areas of software development, such as testing and documentation. It is even more pernicious in the interface because it immediately makes the user feel incapable of using the product. We attempt to avoid this error diligently. One of the bigger challenges in GUI creation is designing for handheld computing devices. The screen size is limited; therefore it is hard to display all useful information simultaneously. Moreover, there is no

obvious way of connecting handheld devices to joysticks or mice for control interfaces. The control interface actually has to be designed on-screen for handheld devices, and that puts more strain on the already limited resource – screen "real-estate".

One of the most common control interface designs for robot control is the use of four soft-keys for forward, reverse, left and right motions, as shown in figure 3.20. [45]

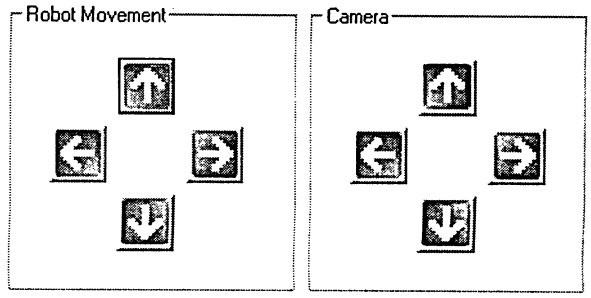


Figure 3.20: A common control interface for telebots

We strongly oppose such a design. These soft-keys can only provide absolute values – Forward, Reverse, Left or Right, instead of subtle gradations. *What about speed control? What about following curves?* Every time the wheelchair must turn, it must stop, turn, and then go forward. This is simply unacceptable for a project like NEPWAK where we want to provide the same resolution of control to the remote controller that the local wheelchair joystick provides. Joysticks have

come to be an ideal control interface for video games, industrial and space robotics. This is because it is a single interface that can provide a metaphor for controlling both the direction of movement as well as the speed.

On our PDA touch screen, we wanted to create a control interface that works like a joystick - a single control for both speed and direction. We achieved this by creating a circular control interface as shown in figure 3.21. Placing the stylus at the centre enable the control, then as one moves the stylus on the interface, the X and Y Cartesian coordinates of the stylus act as the joystick's X-Y coordinates. If the stylus is lifted, or goes out of the control perimeter, the control is disabled and the X and Y values are reset, in effect, the wheelchair stops.

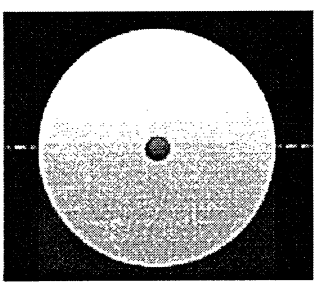


Figure 3.21: Graphical Control Interface

The other important part of the interface is the sensor display. As can be seen to right of the video display (Figure 3.22), the top-view of a wheelchair is drawn. Whenever a proximity sensor triggers, i.e. an obstacle is detected within 80 cms of the wheelchair, the corresponding '**X**' label appears and starts flashing. If the

obstacle comes with in 30 cms of the wheelchair, the label starts flashing rapidly and an audible beep is sounded, and the wheelchair also comes to a halt. Also, if the proximity sensor placed underneath the wheelchair detects a ditch or possible a staircase ahead, the wheelchair immediately stops and the symbol '**VV**' starts flashing with audible beeps.

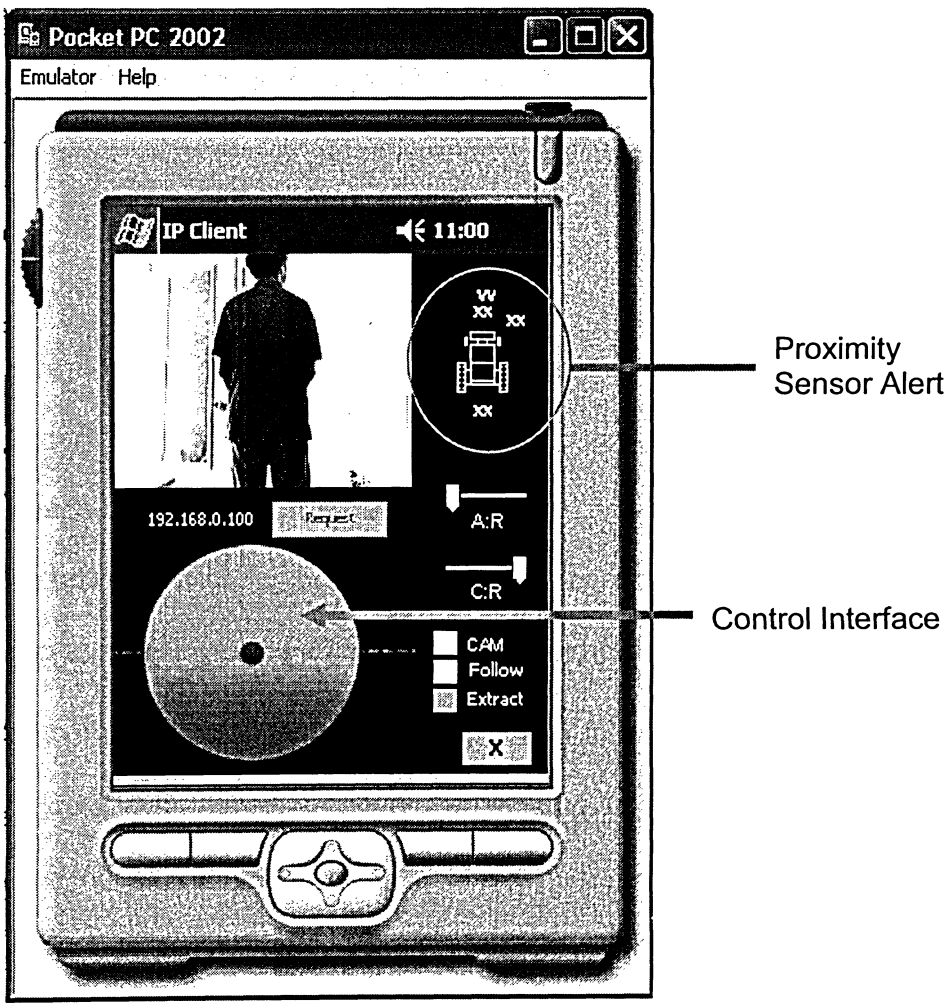


Figure 3.22: NEPWAK PocketPC GUI

Chapter 4 Development Stages & Experimental Results

The development of NEPWAK can be broadly classified into three prototype stages. At each stage we learned from the observed shortcomings of the previous stage and improved NEPWAK's design and added new features as appropriate. In this chapter we will discuss these stages, the experiments we conducted and results achieved. We will also elaborate in greater detail on the experiments we performed with the human tracking and following system.

4.1 Prototype I – Proof of concept

The goal for our first prototype was to develop a system with off-the-shelf hardware and software components and to demonstrate that the remote driving of such a system was at least feasible. We employed the chassis of a discarded yet functional Fortress scientific powered wheelchair. The original seat was removed in order to provide a clear area for prototyping our system (Figure 4.1).

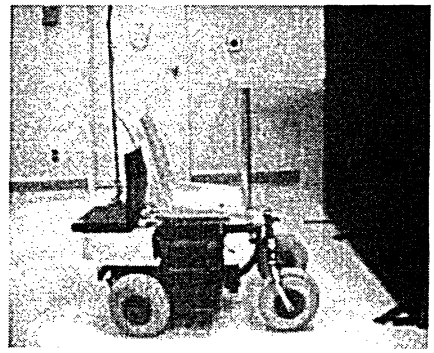


Figure 4.1: NEPWAK first prototype

A laptop computer running the Windows 2000 operating system was used as the wheelchair's server. A simple application was developed in Visual Basic that would accept control commands from a local keyboard and send control data to the parallel port (Figure 4.2).

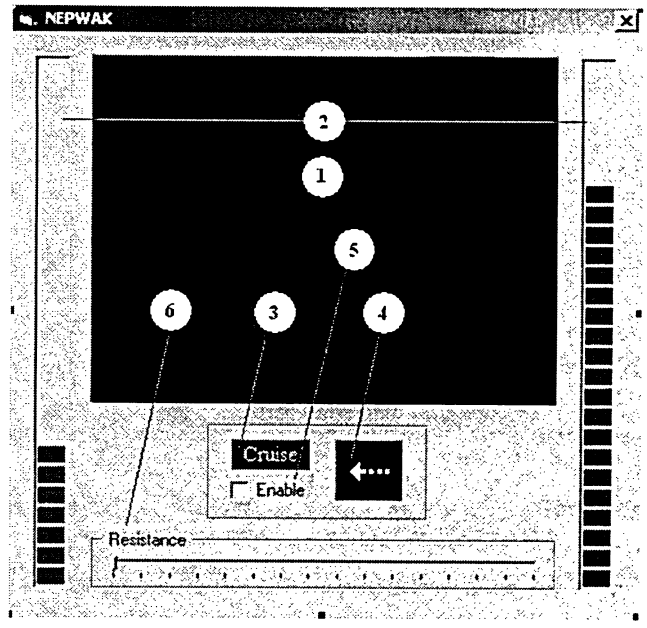


Figure 4.2: NEPWAK Control Interface

Item 1 is the video display from the video feed coming from the wheelchair's camera. Item 2 is one of the status bars indicating the power levels of the wheelchair's left and right motors. Here, the right motor is being supplied with more current than the left, thus running faster. We have provided a "cruise" setting in item 3, allowing the remote driver to continue moving at a certain speed. Item 4 is a direction indicator, here the wheelchair is turning left. Item 5 is

an “enable” switch, when it is checked power to the wheelchair motors is turned on. Item 6 is the resistance slider bar described allowing a degree of momentum to be simulated in the motor responses.

Two four-bit digital to analog converters were used to convert digital data from the parallel port to analog voltages for the left and the right motors (Figure 4.3).

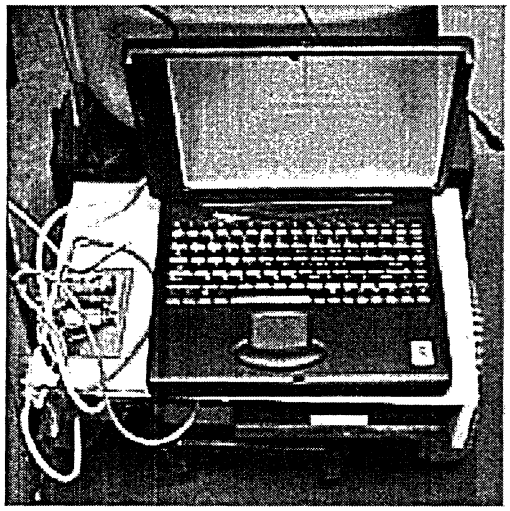


Figure 4.3: Laptop as server with control interface

Video was provided through an onboard USB video camera. Network access was provided via a USB 802.11b Wi-Fi interface card. For test purposes, the video camera along with the Wi-Fi interface card was mounted on a mast behind the wheelchair. The camera was positioned to include a view of the forward extremities of the wheelchair’s occupant to provide the remote operator contextual information (Figure 4.4).

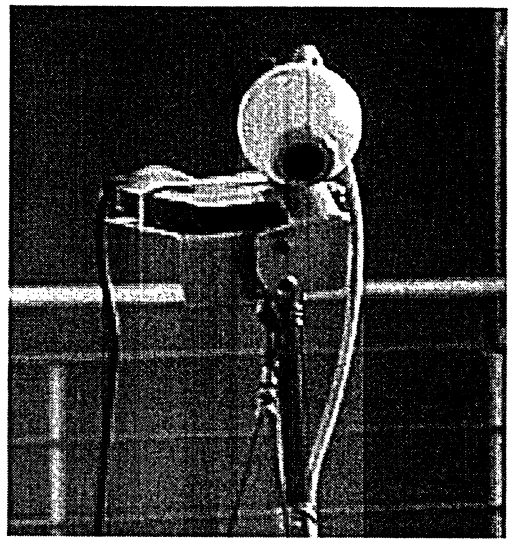


Figure 4.4: Camera and Wireless NIC mast

In order to provide remote control, the NEPWAK application running on the server laptop was accessed through a remote desktop application [90]. A remote desktop application is part of Windows 2000 operating system and is based on Terminal Services which is included in Windows 2000 Advanced Server. It allows using the data, applications, and network resources that are on a remote network terminal. In our case, the laptop computer on the wheelchair acted as the remote terminal server while another network-connected workstation accessed it as a client.

4.1.1 The Trial

The goal of the first test of our system was to demonstrate that the remote driving of such a system was at least feasible. Our intent was to remotely control the

occupied wheelchair from an internal office to a student lounge approximately 200m from the starting location. The test was performed on the heavily used second floor of Ryerson's Rogers Communication Centre (Figure 4.5a, 4.5b).

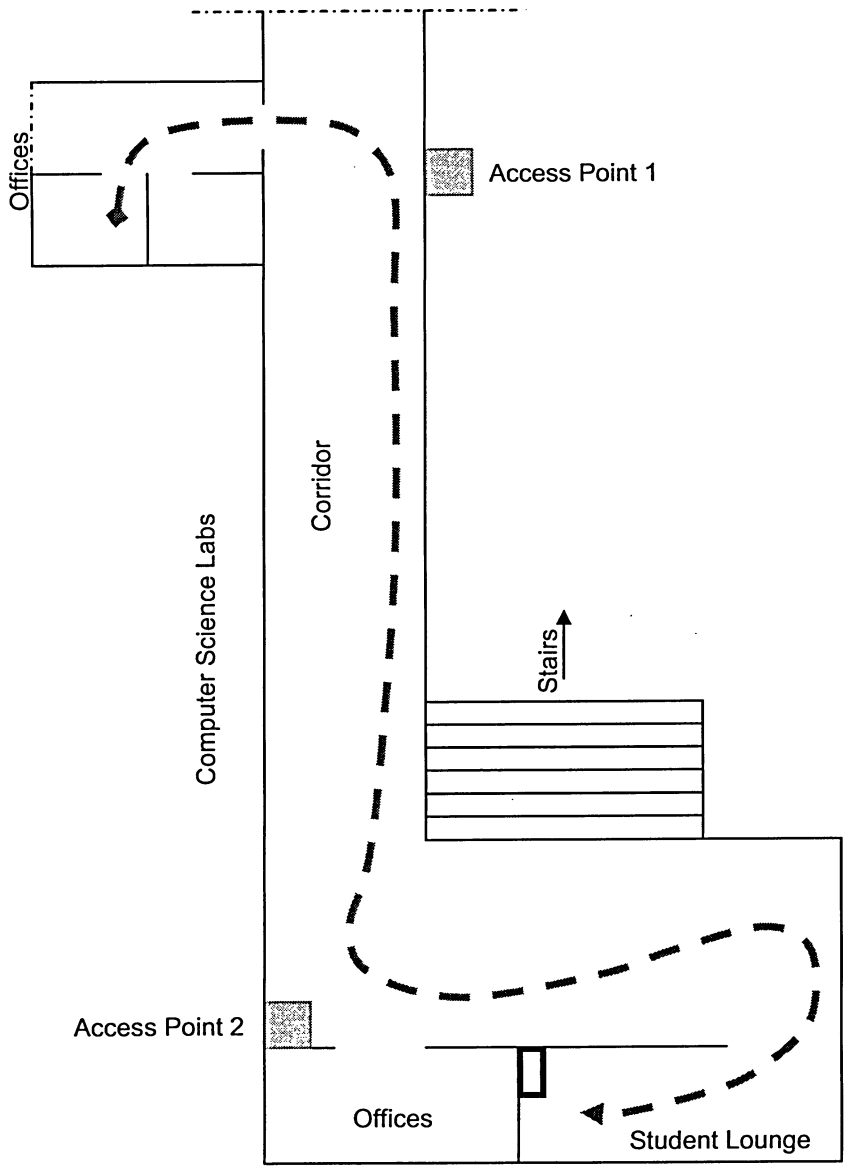


Figure 4.5a: Trial 1 plan

Figure 4.5b: NEPWAK in a busy hallway

The hallway selected was in constant use by students exiting and entering a series of labs along its length. Two network access points (AP) were located near the middle and start of the hallway we used, providing the wheelchair connectivity throughout the test. The remote driver was positioned in another Ryerson building – Eric Palin Hall, and was connected to Ryerson's network through an Ethernet wired connection. The NEPWAK application on the wheelchair's laptop was run using the remote desktop application on the remote driver's workstation.

The remote driver then received the video feed from the wheelchair's camera and manoeuvred the wheelchair using the arrow keys on the keyboard. Over a period of about thirty minutes, the wheelchair was manoeuvred from the office to the goal location (Figure 4.6).

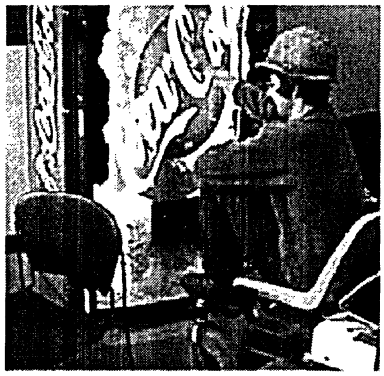


Figure 4.6: Achieving the goal

While we managed to complete the course, we experienced several problems with the system. We had anticipated many of the concerns expressed in [91] however we also observed several other system shortcomings as discussed below:

- **Physical Plant**: A major problem we faced was related to the physical plant of the wheelchair. Our trial chair employed freely turning castor wheels on the front of the chair--as do many other powered chairs of that era (Figure 4.7).

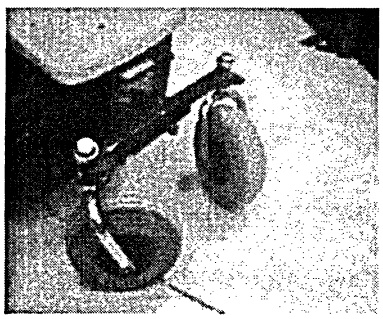


Figure 4.7: Castor wheels on the front

If the driver wished to go straight after turning the wheelchair, the castors would still be in the turned position, as a result the castors would carry the wheelchair in that direction until they had traveled a sufficient distance forward to straighten the castors out thus unexpectedly skewing the path of the chair. This became a source of concern, as the remote driver could not see the castors in the video feed.

- **Resolution of remote control**: The remote driver did not have a good resolution of control. Since we were using the 8-bit parallel port for motor control, only four bits were available for each motor. As a result there were eight forward and seven reverse speeds possible. While this turned out to provide acceptable performance for straight motion, it posed problems while turning or following curves. A higher resolution of remote control was required.
- **Inadequate Visual Information**: Because we employed a single camera without a pan and tilt option, the remote driver was provided with minimal information about the path the wheelchair was following. In fact, the chair's camera was pointed so as to provide a view several meters beyond the chair. This was done for collision avoidance purposes. Despite the fact that the driver was very familiar with the hallway, the chair had several collisions with walls (Figure 4.8), people and the safety rails of the path. Clearly this was an area requiring additional work.

Figure 4.8: Collision during the trial

- **Signal Reduction and Loss**: As the wheelchair moved beyond the radio range of one access point (AP) and towards the second AP it lost the network connection and was stranded. We had to manoeuvre the wheelchair for a few feet towards the second AP via the local joystick before our system reacquired the network connection. This was an unexpected problem and this started our investigation to understand this problem and resolve it.

4.1.2 Network Issues

When we investigated the cause of network connection loss during the trials of this system, we found that the two Access Points (APs) were connected through a distribution system (typically connecting the APs via Ethernet bridges) on a Virtual Local Area Network (VLAN). Thus, both the APs belonged to the same

Extended Service Set (ESS). In such a case the handoff between APs occurs automatically at the link layer, and remains transparent to the network layer [Chapter 2]. Therefore, the handoff in our trial system should have been seamless without any network loss. Since, this was not the case we conducted a simple experiment. We plotted spatial received signal strength (RSS) map covering the entire corridor used in our trial. We observed that there was no overlap in the coverage areas of the two APs. The cause of network loss was therefore a blind spot between the coverage areas of the two APs. When wheelchair reached this spot it lost network coverage and did not reacquire the network until it was manually manoeuvred to within the coverage area of the second AP.

The inter-subnet handoffs are possible only where the APs are connected through a distribution system and converge to the same access router. Large service areas such as that of Hospitals and Extended Care Facilities may be divided into subnetworks. Here, the wheelchair's IP address would become topographically invalid. In such a scenario, as the wheelchair moves from one sub-network to another, it must configure a new IP address, which requires a network layer handoff mechanism.

The Mobile IP working group within the Internet Engineering Task Force (IETF) has developed the Mobile IP [72] protocol. Mobile IP is a network-level mobility

management protocol designed to allow mobile wireless network nodes (MNs) to transparently migrate to different networks without any disruption to higher layer connections. We studied the Mobile IP protocol and created a simulation model based on our first trial system. We were interested in the impact that the network layer handoffs would have on audio/video streaming.

Mobile IP and some of its shortcomings along with proposed solutions (such as Fast-Handover mechanisms) have been previously discussed in chapter 2. In the next section we will present our simulation model and experimental results for Mobile IP and Mobile IP enhanced using the fast-handover mechanism.

4.1.2.1 Simulation Model

The goal of our simulation was to measure the handoff latency for Mobile IP and Mobile IP with Fast-Handover. The handoff latency is the duration over which the client is not able to communicate with the wheelchair. We used Network Simulator version 2 (ns-2) for the simulation. We augmented the base ns distribution (ns-allinone-2.1b7a) [92] with the 'ns wireless extension' module [93] patched to simulate Mobile IP protocol operations. We further extended the simulator with 'Fast-Handover' implementation [94].

The topology used for the simulation experiments is shown in figure 4.9. The link characteristics--the delay (in milliseconds) and bandwidth (in megabits/s)--are

shown adjacent to the links. The access routers have a coverage area of 40 m in radius and are placed 70 m apart, hence an overlap of 10 m between their coverage zones. One TCP source agent is attached to the Client Node (CN) and the corresponding TCP sink is attached at the MN. The TCP packet size is set to 1024 bytes. TCP cross traffic is created between HA and N3, CN and N4 and between BN1 and BN2. We modeled the MN moving linearly between AP1 and AP2 at a speed of 3 m/s (typically the speed of a wheelchair). The TCP cross traffic started at 5s and communication between CN and MN started at 6s simulation time. The MN started moving from oAR to nAR when the simulation time reached 10s. The total simulation duration was 55 seconds.

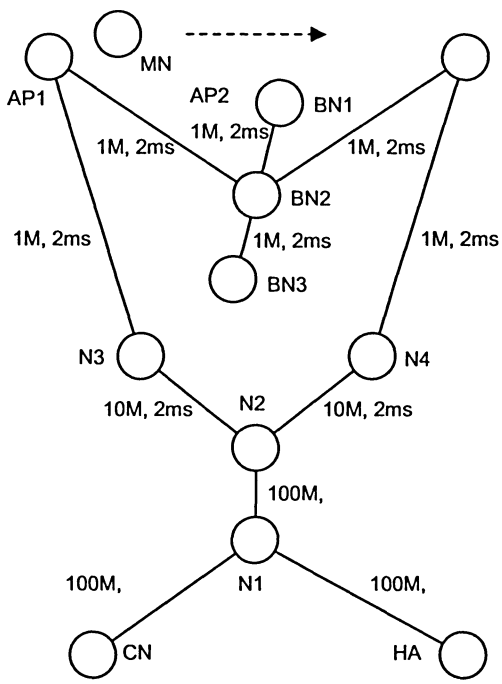
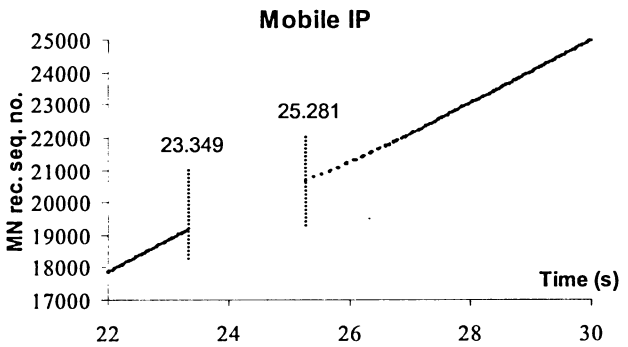


Figure 4.9: Simulation Topology

4.1.2.2 Mobile IP results

Graph 4.1 illustrates the handoff delay for Mobile IP from the perspective of the receiver's (MN) receiving TCP sequence. That is, the curve is plotted between 'Time' vs. 'MN's receive TCP packet sequence number'.

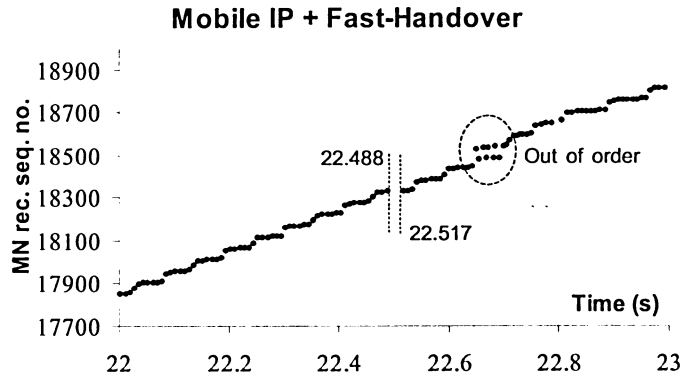


Graph 4.1: MN receiving packets from CN – Mobile IP

From these observations we can see that the MN does not receive any packets between the interval t = 23.349s and t = 25.281s. Hence, the handoff latency (receiver's perspective) for Mobile IP is (23.349 – 25.281) = 1.932s, which causes an outage in communication.

4.1.2.3 Fast handover results

Graph 4.2 illustrates the handoff delay for Mobile IP with Fast-Handover from the perspective of the receiver's (MN) receiving TCP sequence. That is, the curve is plotted between time vs. MN's receive TCP packet sequence number.



Graph 4.2: A MN receiving packets from a CN

From this, we can conclude that the Fast-Handover mechanism provides almost no handoff latency. It was only during the forwarding tunnel establishment stage that MN did not receive data packets for a very small interval of time (22.488 – 22.517) ~ 30ms. This happened because, although the forwarding tunnel was established, it took MN that long to complete the layer two (L2) handoff.

Our investigation into the IP Mobility was with the goal of better understanding of the network behaviour during the wheelchair's mobility. With our experiments and simulation results, we learned that wireless IP networks do support link layer handoff mechanism if the access points are bridged together through a distribution system. However, in very large wireless IP networks, service areas may be divided into sub-networks and we may have no control over their topology. In such cases there is a need for a network layer handoff mechanism such as Mobile IP. Also, through our simulations, we learned that Mobile IP alone

is not an ideal solution as it results in large handoff delays that can severely affect applications such as NEPWAK. An enhancement such as the fast-handover mechanism is required to reduce handoff latency and packet loss during the handoff.

4.2 Prototype II

In our second prototype we improved NEPWAK's design based on what we learned from the shortcomings of our previous system. There were several improvements to the overall design as discussed below:

- **Physical Plant**: In our second prototype we employed an Invacare wheelchair (Figure 4.10). The wheelchair was donated to our research group N-CART [95] for the NEPWAK project. In contrast to our older fortress scientific wheelchair, the Invacare wheelchair had a much better design for our purposes. As can be seen from the figure below, the castor wheels are smaller in size and located behind the wheelchair. This provides a better sense of control for a local driver[1], especially to the remote driver.

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[1] In informal discussions concerning the benefits of front or rear castors with wheelchair users, the consensus was that rear always provided far better control.

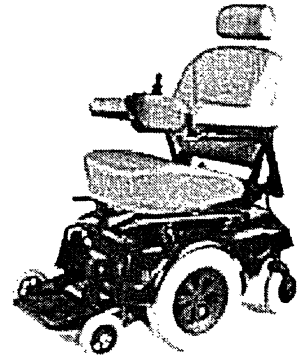


Figure 4.10: Invacare Wheelchair

- **Embedded Computing**: The laptop was replaced by a PC104 Single Board Computer (SBC) running Windows XP Embedded. Instead of using Remote Terminal applications, dedicated client and server applications were written in C++ .NET supporting Video, full-duplex Audio and control streaming. The figure 4.11 below shows the arrangement of the PC104 board behind the wheelchair.

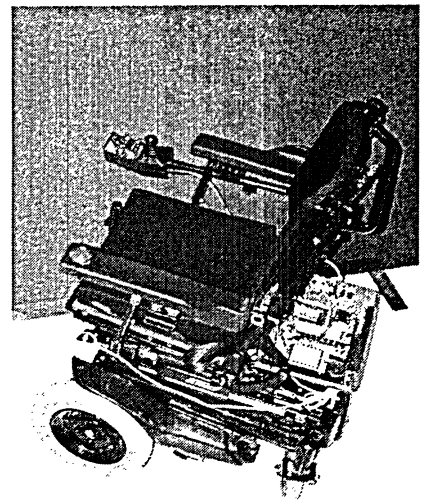


Figure 4.11: PC104 SBC located behind the wheelchair

Figure 4.12 shows the dedicated client application for remote control on a workstation.

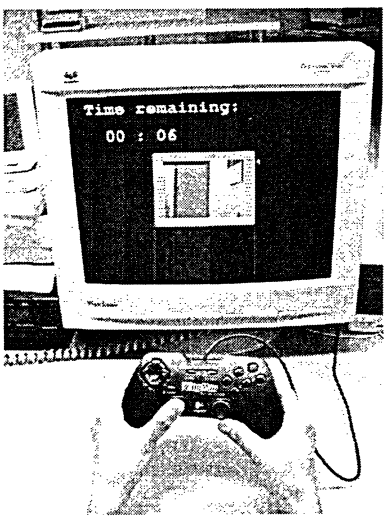


Figure 4.12: NEPWAK prototype II, remote driver interface

- **Resolution of remote control**: The resolution of remote control was greatly improved. Instead of the keyboard, a joystick was employed as the controller on the workstation client. On the wheelchair side, instead of using an 8-bit parallel port to control motor speeds, a dedicated control module was developed. The control module is based on a PIC microcontroller that receives control commands through the PC104 serially and generates Pulse Width Modulated (PWM) signals for motor control. Please refer chapter 3 for further details.
- **Camera Position**: Based on the usability feedback from our first prototype trials, we repositioned our video camera on the wheelchair. Instead of placing the camera on a mast, it was placed below the seat and above the left wheel

mudguard. The position of the camera is shown in figure 4.13. In this position, the remote driver had a much better view of the path ahead.

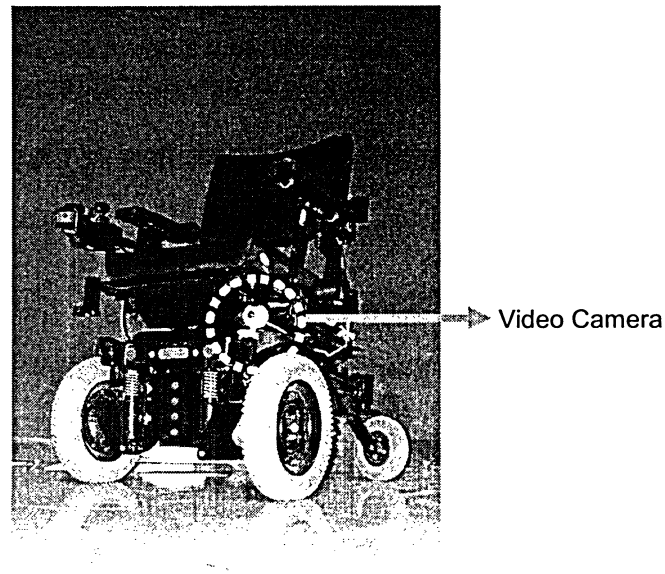


Figure 4.13: Position of camera

- **Signal Reduction and Loss**: We realised that in order to prevent the wheelchair from going out of Wi-Fi coverage, the remote driver needs a very important piece of information – Wi-Fi Received Signal Strength (RSS). In our second prototype, we measure the RSS at the wheelchair and then stream the RSS value to the remote client. The remote client is therefore always aware of the signal quality at the wheelchair and is automatically warned if the quality drops below 60%. This prevents the remote driver from unknowingly driving the wheelchair out of network coverage and potentially endangering

the wheelchair's occupant who might not be able to bring the wheelchair back.

4.2.1 The Trial

NEPWAK's second prototype won the annual Digifest [96] competition in 2004 and we were asked to create a demonstration at the Ontario Science Center (OSC) [97] for one week. This was our biggest opportunity to test NEPWAK in a public venue and gather much needed feedback from people using the system. We were interested in gathering feedback on ease of control, video streaming quality and the overall user experience. In order to interest visitors in using NEPWAK our installation was organised as a game involving two people (subjects).

The wheelchair was placed inside a rectangular enclosed area about 15 x 20 feet in size. Five inflatable dummy targets (boso clowns) were randomly scattered by our staff in the area. One subject was given an inflatable base-ball bat and would sit in the wheelchair, while the other (the remote driver) was given the NEPWAK workstation remote control. The remote driver did not have a direct view of the wheelchair but received the video & audio feeds from the NEPWAK system. The game was very simple. The subject in the wheelchair had to hit as many targets as possible in one minute. The remote driver--based on the video feed and audio link from NEPWAK--would attempt to manoeuvre the wheelchair so as to

maximize the number of clowns hit. This was a cooperative game and a good usability test for us. Figure 4.14a shows the trial plan, and 4.14b is an actual picture of the game.

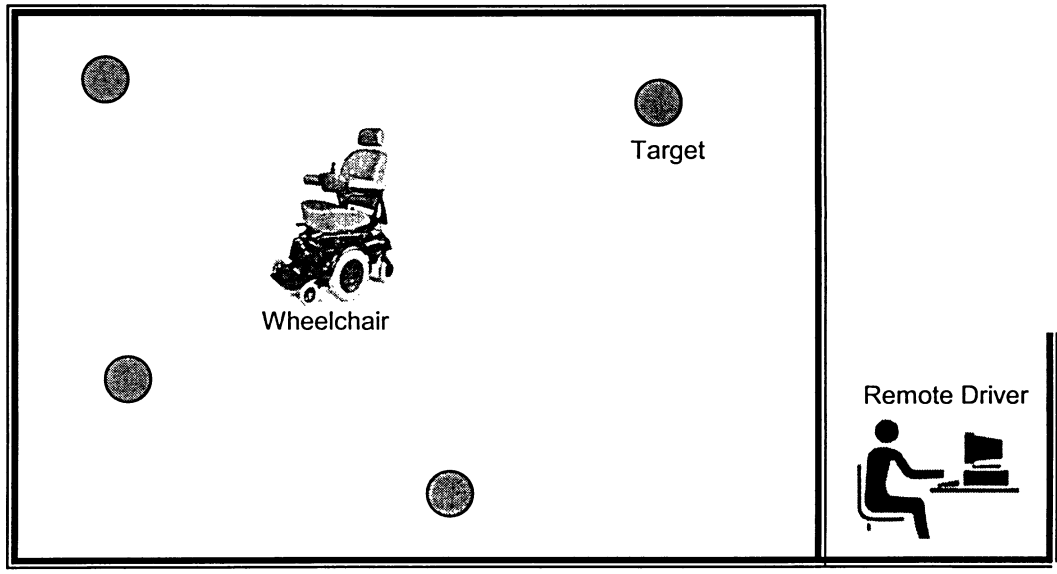


Figure 4.14a: The trial plan at OSC

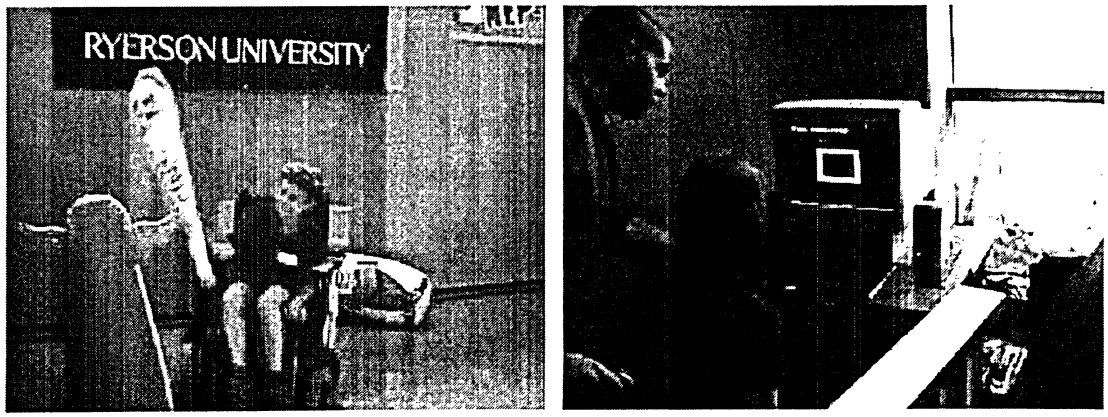


Figure 4.14b: Prototype II in test at OSC

Over a period of one week more than two hundred people tried NEPWAK and overall we received very positive feedback. People from engineering and medical backgrounds tried the system and provided very valuable suggestions. During the week, seventy-six feedback forms were collected from those who tried the system and those who wanted to contribute their ideas. The feedback questions used are provided in Appendix D.

Below, we've summarized the overall rating of our system and listed some very valuable suggestions received:

Topic	No. of Complaints	Comments
Video Feed	39 / 76	Video is slow, jittery and delayed.
Viewing Angle	26 / 76	Narrow Viewing angle, need for some way to move the camera.
Control	17 / 76	Control is slow or delayed and sometimes doesn't work the way expected.
Audio	0/76	Generally not mentioned although all participants used it
Overall Rating	76 / 76	Mean Overall Rating = 7.8 / 10.

Table 4.1: Prototype II Trial User Feedback

- **Video Feed**: A very common complaint from the users was that the video feed was delayed, slow and jittery. We had experienced this problem ourselves and video definitely required more work.

- **Viewing Angle**: Another very common concern was that the remote driver had a very narrow viewing angle. Several suggestions regarding implementing camera motion in the form of a pan-and-tilt camera system, or repositioning the camera were received. Some users also mentioned that the camera view was partially occluded by the left leg of the person riding the wheelchair.
- **Control Interface**: While no one had any complaints about the kind of control interface, A few comments were received regarding the control being slow or delayed.
- **Overall Rating**: A mean overall rating of 7.8 / 10 was received from the seventy six feedback forms collected.

Some other feedback comments from people with engineering backgrounds were about implementing proximity sensors around the wheelchair and providing some autonomous behaviours such as wall following and obstacle avoidance. At that time we were already working on implementing proximity sensors but it was good to have encouraging commentary.

4.3 Prototype III

NEPWAK Prototype III was designed with the goal of removing the shortcomings observed in prototype II and implementing autonomous behaviours such as

obstacle avoidance and human following. Modifications introduced in this design release were as follows:

- Human Tracking and Following System
- Video Optimization

We will now discuss these additions, experiments conducted and concerns observed along with their possible solutions.

4.3.1 Human Tracking and Following System

Our human tracking and following system is a fusion of two independent techniques – A WiFi-based technique and a Color-Blob-based technique. These techniques, along with the fusion algorithm, were discussed in chapter 3. Here, we will present our experimental results for these two independent *Human Tracking Systems*. Then we will discuss the implementation of our *Human Following System*. Thereafter we will discuss our experimental results on Human Following.

4.3.1.1 Wi-Fi Based Human Tracking System

In our first experiment we plotted the variation of the received signal strength (RSS) with distance. A person carrying a PDA was positioned in the middle of a corridor 275cm wide. Using our directional antenna RSSI values were recorded

every 10 cm for the first 2 m and thereafter, at every meter for 10 meters. The antenna was pointed towards the PDA at all times (Figure 4.15).

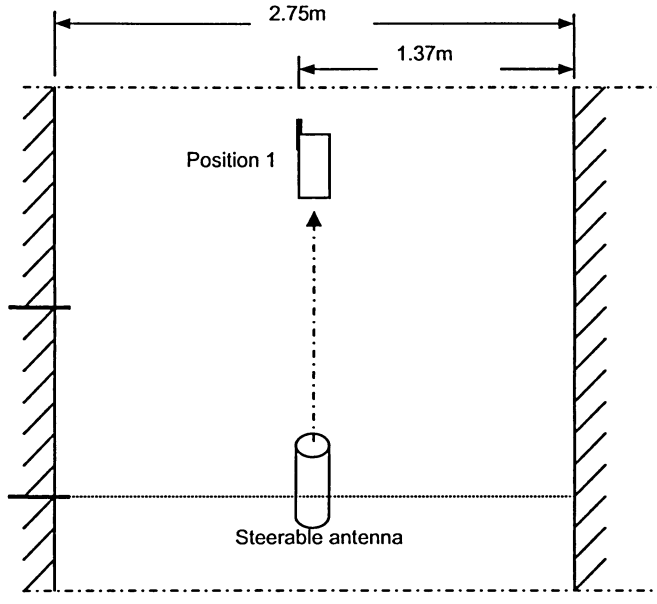
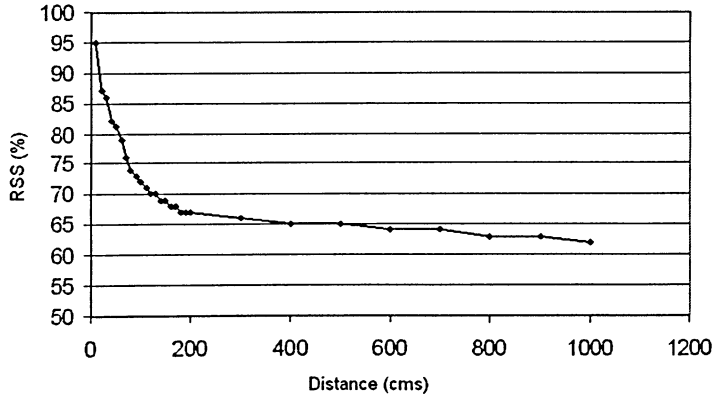


Figure 4.15: 'RSS variation with distance' setup

The results were plotted in Graph 4.3.



Graph 4.3: Variation of RSS with distance

We observed that the RSS does not vary linearly with distance. It decreased rapidly in the first 3 m and showed a very gradual decrease thereafter. As a result of this the Wi-Fi system does not provide a very accurate measure of the distance of separation beyond 3 m.

In our next set of experiments, we mounted the directional antenna on a stepper motor and performed 115° RSS scans at various distances and positions from the PDA. Figure 4.16 illustrates the case when the steerable antenna was placed at a distance of 2 m from the PDA (position 1). A 115° scan was performed in anti-clockwise direction and recorded RSS values were plotted against angular positions of the antenna (see graph 4.4).

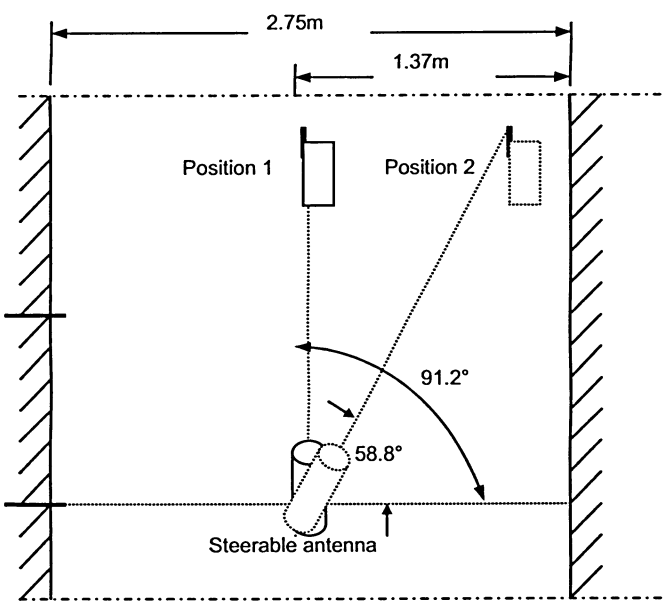
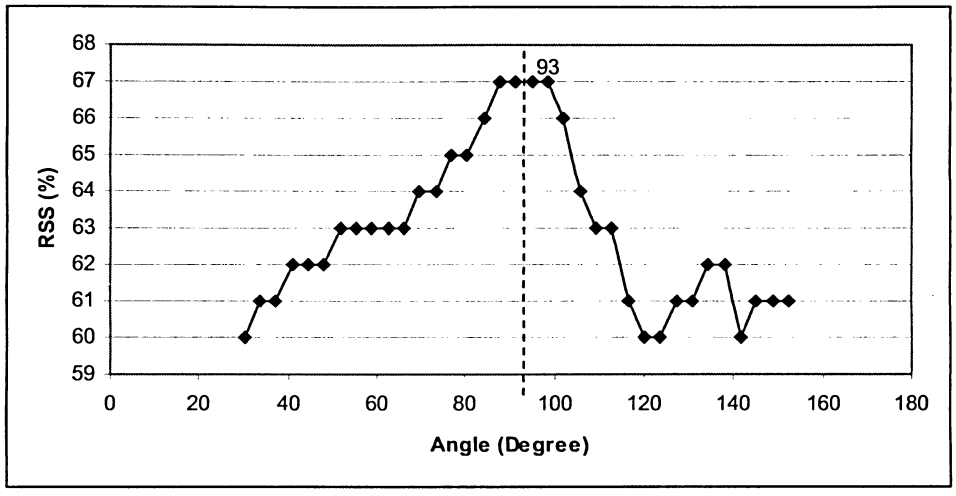
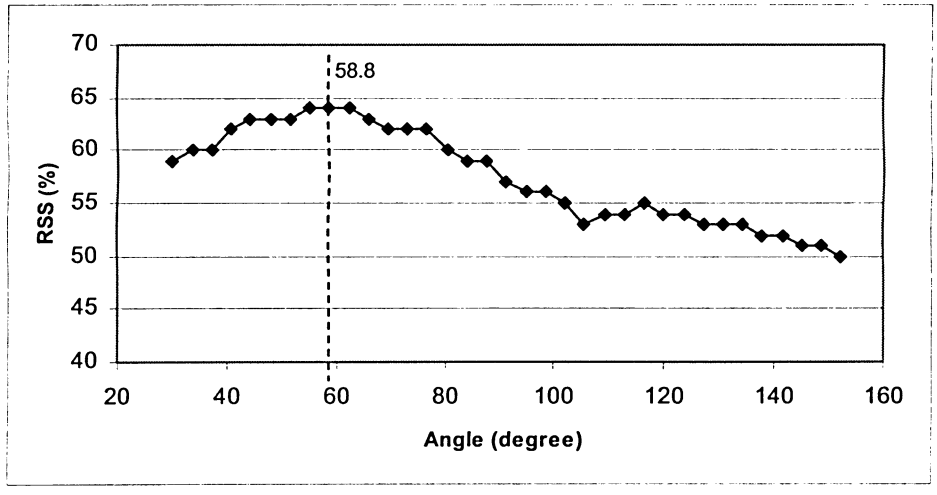


Figure 4.16: RSS scan setups



Graph 4.4: 'Angle vs. RSS' graph for position 1 (2m)



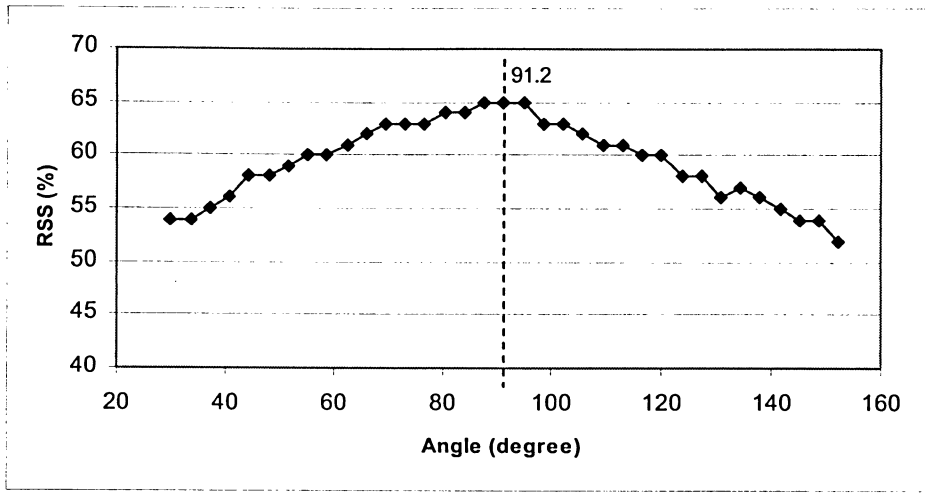
Graph 4.5: 'Angle vs. RSS' graph for position 2 (2m)

A second scan was performed when the PDA was placed at position 2. The recorded values were plotted in graph 4.5. From graph 4.4 it can be observed that the Peak Angle is 93° the RSS was 67%. If we look at figure 4.16, the PDA

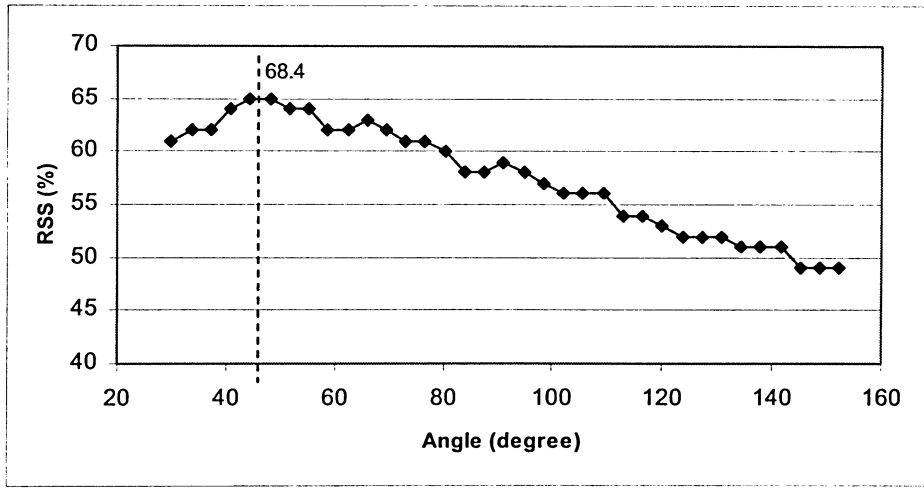
is placed straight ahead of the antenna, when the antenna conducts a scan in anticlockwise direction the peak is expected at 90°. Therefore an experimentally determined peak angle of 93° is fairly accurate. The fact that the angle will be translated to form a "Region of Interest" (ROI) reduces the need for fine granularity of accuracy. In other words, the experimental results are accurate enough for our purpose.

When the PDA is moved to the side (position 2), we see that the peak RSS value is also shifted (Graph 4.5), now at an angle of 58.8°. We clearly see that the Wi-Fi tracking system can accurately determine the direction of the PDA. However, it is not capable of providing accurate distance information.

Next, we repeat the above experiments at different separation distances i.e. at 4m and 8m of separation between the PDA and the antenna. Graphs 4.6 and 4.7 are results from 4 m of separation, while graphs 4.8 and 4.9 are results from 8 m of separation.

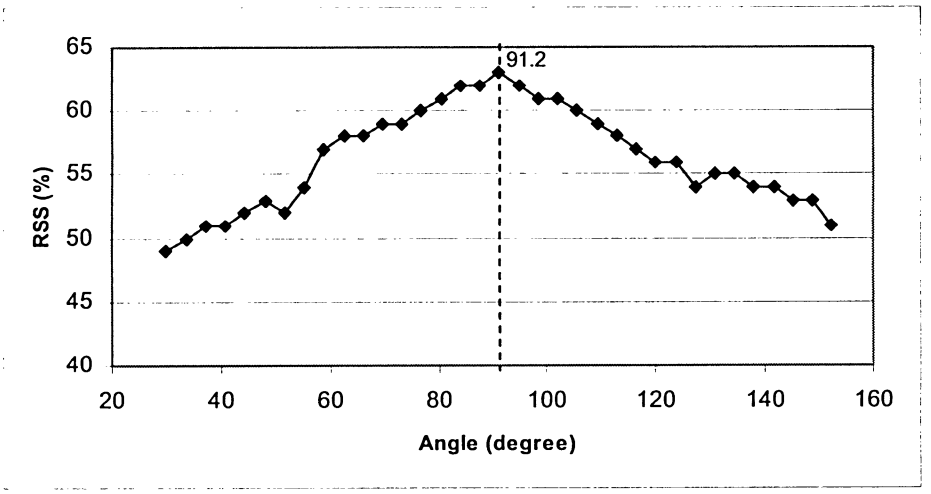


Graph 4.6: 'Angle vs. RSS' graph for position 1 (4m)

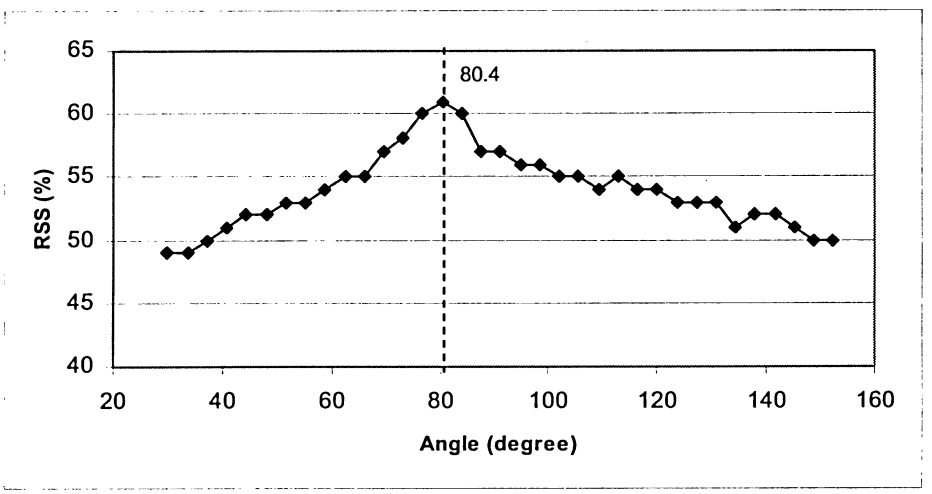


Graph 4.7: 'Angle vs. RSS' graph for position 2 (4m)

From the graphs above we can note the shift in the peak when the PDA is moved from position 1 to position 2 at 4m of separation.



Graph 4.8: 'Angle vs. RSS' graph for position 1 (8m)



Graph 4.9: 'Angle vs. RSS' graph for position 2 (8m)

Again, we see that the peak shifts consistently when the PDA is move from position 1 to position 2 at 8m of separation. Thus we see that Wi-Fi based tracking system provides very consistent and accurate tracking results.

4.3.1.2 Image Processing-Based Human Tracking System

In this section, the colour-based tracking system is experimentally verified. For our purposes we used still images that were recorded in 3 RGB colour with the aid of a commonly available web cam. The digitization was done in 8 bits per colour, hence 24 bits per pixel. In essence, this provided us a test rig that decoupled the image processing system from reliance on the video transmission system on NEPWAK.

Two 40W fluorescent tube light sources of 2,150 Lumens intensity were used to illuminate the scenes. The size of the test images were 160 x 120 pixels. The images used are shown in figure 4.17a through d. The images are not ideal for classical image processing as they are "Contaminated" by shadows.

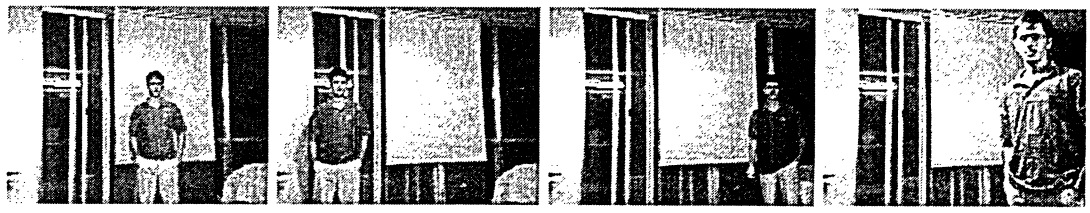


Figure 4.17a, b, c, d: Raw images used for the tracking experiment

As discussed in chapter 3, the image processing-based tracking system has several stages: Start-up, Search, Acquisition and Lock. These stages are implemented as 'methods' of a 'PersonTracker' class written in C++ .NET.

During the start-up phase, the person, looking at the video feed on the PDA, stands approximately 2 m in front of the camera. He positions himself so that his T-Shirt occupies the rectangular region as shown in figure 4.18.

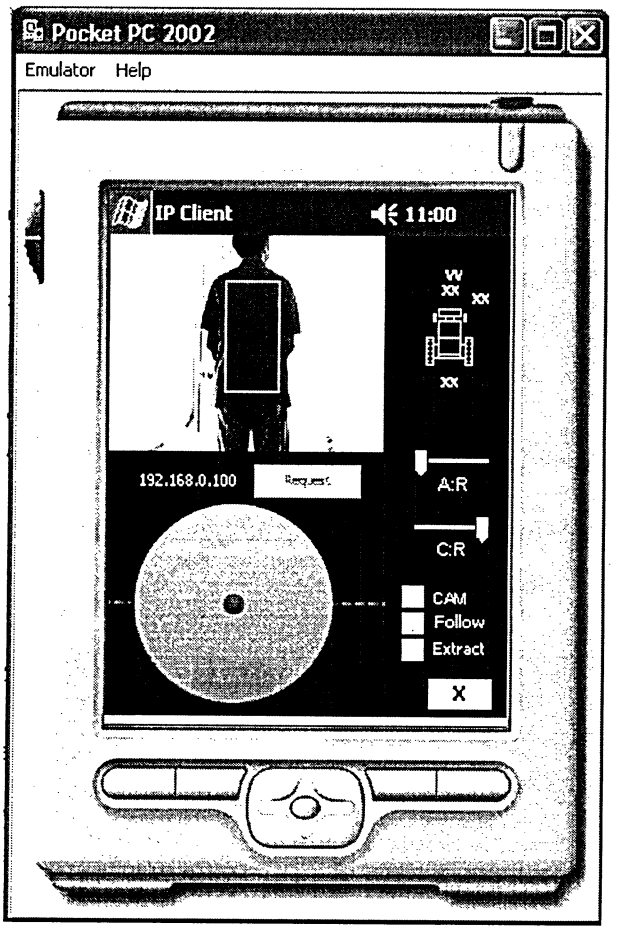


Figure 4.18: Start-up phase

As a first step, the shirt is classified as Red, Blue or Green whichever forms the highest component of the uni-coloured shirt. Then, the high and low thresholds (C_l, C_h) of the shirt's colour are determined. For images shown in figure 4.18, the

color of the shirt was classified as Red. In this case, the red high and low thresholds (R_l, R_h) were calculated to be 0.6 and 0.8 respectively. Thereafter, the Search, Acquisition and Lock methods were tested as below:

Search: This method searches through all the 32 vertical regions of the image to look for 10 vertically continuous pixels that lie within the high and low color thresholds. For illustration purposes, the method marks the Column that it finds these target pixels in with a white line. The method was run on all the 4 test images shown in figure 4.17 and the results are presented in figure 4.19 a, b, c and d respectively.

Figure 4.19: Search method test results

As we can see from the above results, the search method successfully finds the first ten vertically continuous red pixels in each picture. This basically marks the beginning of a color blob and is used by the Acquisition method to acquire the target.

Acquisition: The acquisition method takes the region of the 'first ten vertically continuous pixels' as an argument. It then locates all the continuous target pixels in and around that region and forms a "best fit" rectangle around them. If the aspect ratio of the rectangle lies within a specified range, then the target is said to be acquired.

In our next set of experiments we ran the Search method followed by the Acquisition method on the images in figure 4.17. The results are displayed in figure 4.20 below:

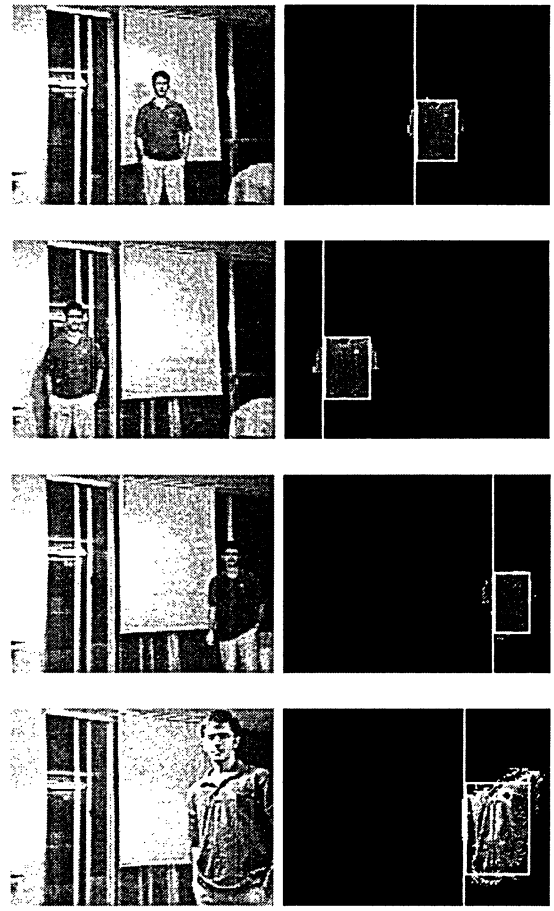


Figure 4.20: Search and Acquisition method test results

As can be seen from the above results, the person's shirt is successfully acquired in all the four cases. To further test the acquisition stage, we captured the image in figure 4.17a and drew a solid square with the same color as that of the shirt to the left of the person (Figure 4.21a). We created another picture by drawing a solid rectangle with aspect ratio of 1.9 to the left of the person (Figure 4.21b).

Figure 4.21a: Solid Square drawn to the left of the person

Figure 4.21b: Solid rectangle (aspect ratio = 1.9) drawn to the left of the person

Our intention was to simulate conditions when there are two color blobs in an image that will pass the search stage. For example, an object appears in the image whose color matches the shirt of the person being tracked. In another scenario, two people wearing the same coloured shirts appear in the image; as can happen in hospitals full of attendants wearing green or blue uniforms. Our implementation of the tracking system will still be able to track the correct person. This claim is based on certain assumptions:

1. No intermittent targets, i.e. person being tracked will not disappear and re-appear in another location in consecutive image frames. This is a possibility if

a person's image is obscured by another object in the frame such as a structural pillar or a door.

2. This is a cooperative tracking and following system, i.e. the person being tracked will assist in being tracked by maintaining a natural walking gate of 1.4 m/s as much as possible and will not attempt to "lose" the wheelchair. Also, the tracked person will attempt to stay in the Line of Sight of the camera to avoid target loss.
3. The success of the tracking system relies on measurements conducted during the start-up phase. We assume that the start up phase was completed successfully and that a consistent lighting level is maintained. This may not be practical in all cases but this eventuality is beyond the scope of this thesis.

The results obtained by running the Search and Acquisition methods on images shown in figure 4.21a are shown below (Figure 4.22a)

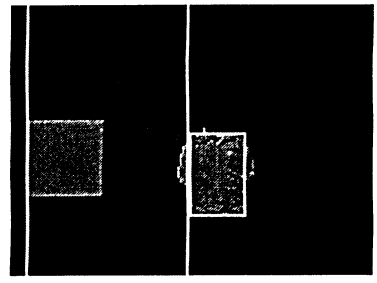


Figure 4.22a: Search and Acquisition Results – two color blobs

We can see that the Search method found both the blobs, but only the person's shirt was acquired. This is because the search method first found the solid square. However, the square did not qualify as a valid target in the Acquisition method because its aspect ratio doesn't lie within the desired range. This triggered a complete search through the remaining portion of the image as a result the person's shirt was located. The Acquisition method then acquired the shirt as it met the aspect ratio requirement. The system uses the aspect ratio as a heuristic to help ensure acquisition.

Let us now analyze the results (Figure 4.22b) of the Search and Acquisition methods on figure 4.21b:

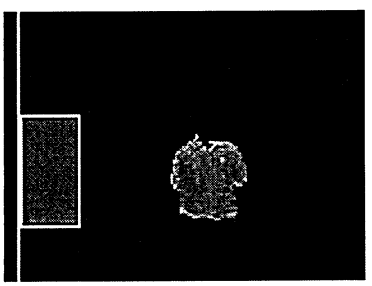


Figure 4.22b: Search and Acquisition Results – two color blobs

We see that the wrong target is acquired. This happened because the solid rectangle meets the aspect ratio requirement of the Acquisition method. In order to avoid such situations we use our concept of target lock. According to target lock, the Search method starts searching from the region where the target was acquired in the previous frame. As a result, if a correct target is acquired once, its

acquisition is maintained even in the presence of other eligible color blobs in the image. However, if the wrong target is acquired, its acquisition will be maintained for a period of less than one second. This is because the Wi-Fi system completes its scan and provides an accurate ROI every second. In the worst case scenario, if the target is lost on both the tracking systems the wheelchair stops and the PDA client receives a failure message and appropriate action can be taken without endangering the wheelchair's occupant.

4.3.1.3 Human Following System

After detecting and locating the target person using our two-tier tracking system, we use a simple yet elegant reactive following behaviour. The region in front of the wheelchair, as seen from the camera, is considered to be divided into five zones. Depending upon which zone the person is located in and at what distance, the NEPWAK uses a combination of speed and turning curvature to follow the person. The goal of the following system is to maintain the initial distance of separation (distance measured in the start-up phase) and to keep the wheelchair aligned in the direction of motion of the person being followed. Figure 4.23 below, explains the following system.

The table 1 below describes the width of the zones and the action the robot takes when a person is located in any one of the zones:

Zone	Width (pixels)	Action
1	20	Sharp Left
2	35	Slight Left
3	50	Straight
4	35	Slight Right
5	20	Sharp Right

Table 4.2: Description of zones

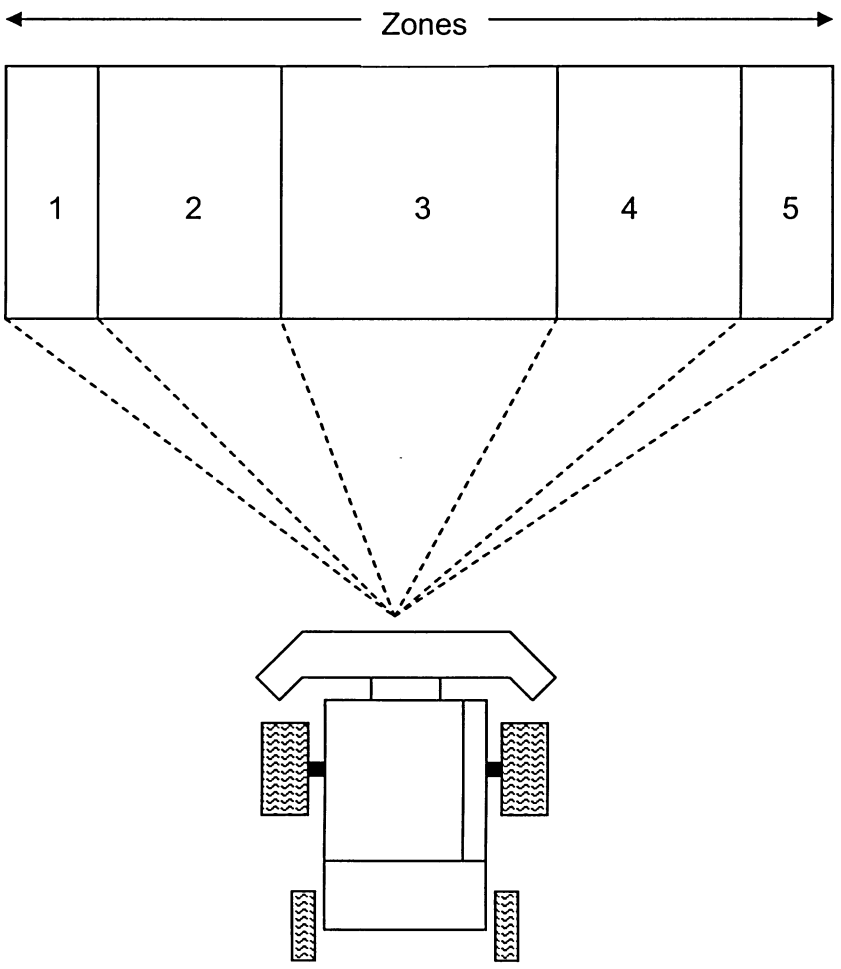


Figure 4.23: Person following – Zone description

Besides the direction of motion, the NEPWAK also has to control the speed of the wheelchair to follow the person at a safe distance and to accelerate or decelerate based on the distance of separation. In order to do this, the following system uses the height of the best-fit rectangle around the tracked color blob as a measure of distance. The pseudo code below describes the relationship between the height of the rectangle and speed of the wheelchair:

Let Hi be the initial height of the rectangle at the start-up phase, then:

If **(0.7 x Hi) < Current Height < (0.9 x Hi)**; then **Speed = Medium**

Else if **Current Height > = (Hi)**; then **Speed = Stop**

Else if **Current Height > = (0.9 x Hi)**; then **Speed = Slow**

Else if **Current Height < = (0.7 x Hi)**; then **Speed = Fast**

The algorithm above provides sufficient accuracy for simple distance estimation in order to decide whether the wheelchair has to accelerate to decelerate. The experiments conducted using this algorithm produced very successful results [98] in straight paths as well as in turns. However, we noticed slight problems during sharp turns. If the person being followed turned sharply the result was target loss. The following figure illustrates the problem:

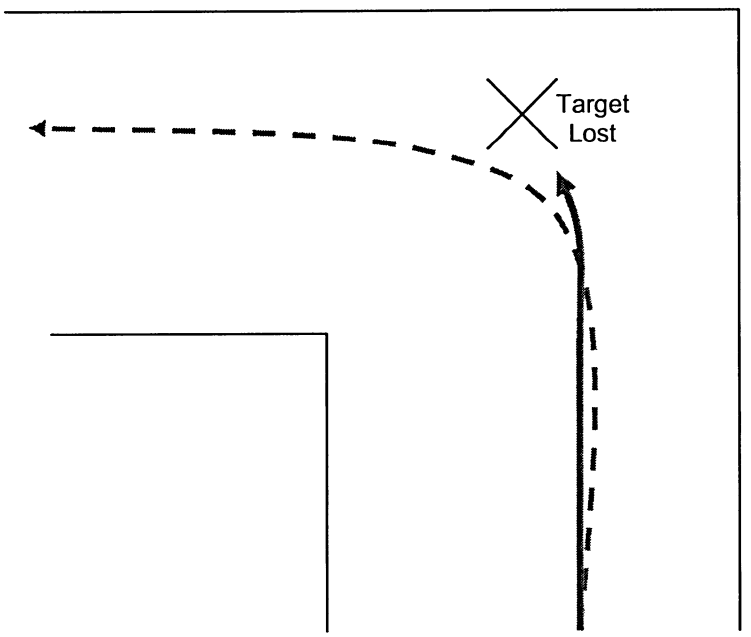


Figure 4.24a: Target lost during sharp turns

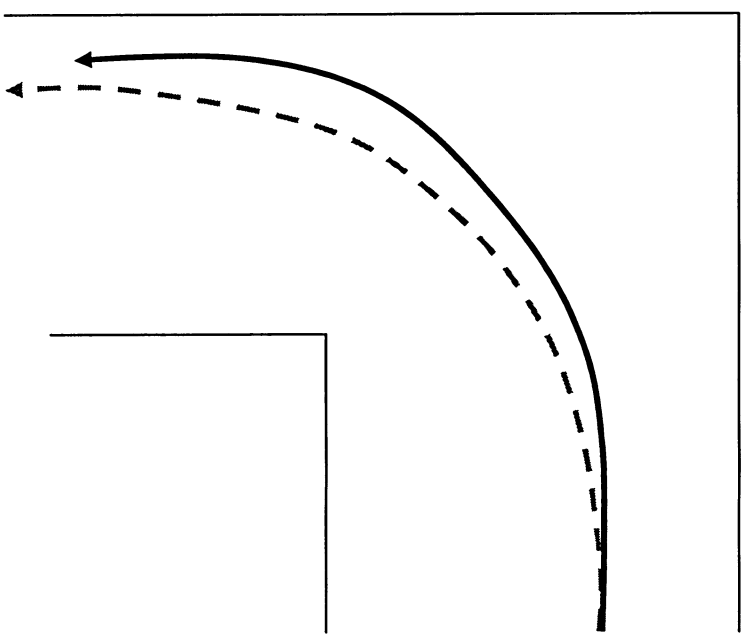


Figure 4.24b: Successful turn during human following

Figure 4.24b shows the correct path that the person should follow to result in successful turns during NEPWAK's human following operation. While this is a concern, we believe this problem can be overcome through simply training the person being followed to not make sharp turns.

4.3.2 Video Optimization

Based on feedback received during NEPWAK's prototype II demonstration at the Ontario Science Centre, we optimized NEPWAK's video streaming to reduce the inter-frame delay and jitter in video playback at the client [99]. In order to approach the problem we conducted a simple experiment. We setup the server and the client software to measure the video capture and playback frame rates respectively. We averaged the frame rate over a period of ten seconds and observed that the frame rate was eight frames per second at each end. At that time we were capturing the Video at 320 x 240 pixels (frame size) and were displaying it at the same size on the workstation client. Average video frame after JPEG compression was approximately 6 Kbytes in size.

Since, display frame rate at the client was equal to the capture frame rate at the server and since we were not buffering video at the client, it was obvious that the network was not the bottleneck. Instead, it was the webcam drivers that were unable to provide a fast video capture rate. However, when we configured the camera to capture image frames at half the previous image size i.e. at 160 x 120

pixels, we saw an immediate improvement in the capture rate. The capture rate improved from eight frames per second to twelve frames per second. With this we also observed that the CPU usage dropped by almost 20% from a pervious value of 80% to 60%. This meant that the webcam drivers were originally capturing the video at 160 x 180 frame size and were resizing the image through software to produce a frame size of 320 x 240 pixels. It was therefore the resize process that was CPU intensive and was causing a reduced capture rate.

Although reducing the frame size improved the video frame rate, an image size of 160 x 120 pixels was very small for the workstation client with the screen resolution set to 800 x 600 pixels. Therefore, on the client side we used the .NET's Bitmap library to resize the image to 320 x 240 pixels frame size for playback. Since we were using a faster CPU – an AMD 1GHz on the client side, the resize process did not have a noticeable impact on the performance. In essence, we moved the CPU intensive image resize process from the server to the client in order to improve the video performance, the result was a 50% increase in the frame rate.

Chapter 5 Conclusion and Future Work

This research project has resulted in the development of a kit – "Network Enabled Powered Wheelchair Adapter Kit" (NEPWAK) that can be retrofitted to any commercially available powered wheelchair--augmenting it with the potential for remote health care and control. NEPWAK provides mobility and remote health care to individuals who otherwise could not independently use a standard wheelchair due to motor, sensory, perceptual, or cognitive impairments. We have introduced techniques for modifying and using commercially available powered wheelchairs as mobile platforms enabling communication and remote control. This is an ideal platform for the deployment of tele-health services within homes and healthcare facilities.

Medical professionals and engineers who tried and learned about the NEPWAK project at its week-long demonstration at the Ontario Science Centre were excited by the possibility of such a system. They saw a potential for the system being used in healthcare facilities and homes for remote care and assistance. Ease of patient transport is also the potential advantages that NEPWAK provides for hospitals.

NEPWAK has been designed in an academic-engineering setting and its development can be broadly classified into three prototype stages. At each stage

the system was thoroughly tested and we learned from its shortcomings, improving the design at each stage. In its current state, it is a robust, reliable and relatively safe remote control system providing video, full-duplex audio and remote control services over WiLAN networks. Some of the facilities of NEPWAK could put humans in danger therefore it provides the following features to ensure safety and reliability:

1. Local Control Override: Local joystick can override remote control commands.
2. Obstacle Avoidance: NEPWAK is equipped with peripheral Infra-red proximity sensors. The system detects obstacles within 80 cms range of the wheelchair, both in front and back.
3. Received Signal Strength: So that the remote operator does not drive the NEPWAK equipped wheelchair out of the network coverage, he is provided with the Wi-Fi received signal strength (RSS) as measured at the wheelchair.
4. Client Authentication: All clients are authenticated during connection requests using a ten byte authentication key unique for every client.

Besides remote control and communication services, NEPWAK prototype III also provides autonomous features such as obstacle avoidance and a novel human following system to ease patient transport where this feature may be useful.

The obstacle avoidance system, though operational, requires more work to enhance safety. At present we are using five infrared proximity sensors for obstacle avoidance, they do not cover the complete periphery of the wheelchair thus leaving blind spots. We would like to incorporate mixed Infra-red and Sonar sensor ring around the wheelchair to allow obstacle avoidance on all sides.

NEPWAK's human tracking system is novel. It is based on two independent tracking systems that provide very accurate and robust tracking results. The human following system on the other hand, is fairly simple and we are considering additional work in the area. At present, NEPWAK has a reactive-following system; through experiments we identified a shortcoming of the system as described below.

Looking at figure 5.1 below, let us consider that the person being followed is at 'point A', and at that instant the wheelchair is at 'point B', following the person at a safe distance. In order to avoid the 'obstacle X', the person turns right. The wheelchair also follows the person and turns right at point B. As we can see, this reactive behaviour will cause the wheelchair to head towards obstacle Y. The wheelchair will eventually stop when the obstacle is detected by the proximity sensors but the target will be lost and the chair will have to be manoeuvred through remote control.

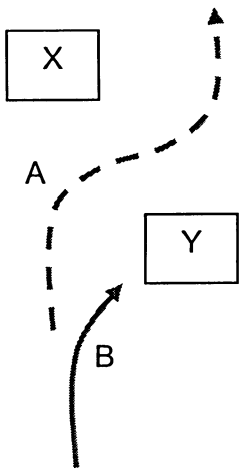


Figure 5.1: Reactive following system

Thus we see that reactive following is not the best approach in certain situations, we are interested in implementing a mechanism that we call 'Delayed Reactive Following'. If the wheelchair could track the motion of the person ahead and react to it after an appropriate interval, it could solve the above problem. The idea is to follow the foot steps of the person to result in an exact following behaviour. This means that instead of turning at point B, the wheelchair would track and record the motion of the person and turn when it reaches at point A – thus the name 'Delayed Reactive Following'.

As well as providing technological enhancements, we are interested in evaluating NEPWAK in a medical setting. We wish to introduce the project in a health care facility to be tried and tested by patients who might benefit from NEPWAK. We would like to work with occupational therapists to identify areas that may require

more work – such as provisioning of tele-health services by using medical sensors on NEPWAK. In an effort to do that, we conducted a survey [100] to collect a wide range of feedback on the current prototype. All feedback was collected through interviews. Interview subjects included severely disabled individuals who might benefit from NEPWAK, occupational therapists, and others who have had experience working with disabled individuals. Interviews were conducted as open-ended "question and answer" sessions which sought to explore issues, including (but not limited to): feasibility, target market, safety issues, and potential usability improvements.

Powered Wheelchair users had a negative reaction to NEPWAK—and continue to do so, and there was very little interest expressed in utilizing the technology. Safety issues and a sense of safety were also a primary concern. The general opinion was that trust would have to be established between the remote operator and the chair's occupant. There was also a general mistrust of the technology. There was a concern that such a system has the potential to remove independence from a wheelchair occupant and some individuals saw this as a threat.

At the moment we are unable to objectively comment on these attitudes as we do not have enough data concerning how individuals might employ such a system in actual use. We also must point out that the NEPWAK technology is not geared

toward current wheelchair users. Instead it might be most beneficial for severely handicapped people who at present cannot operate a standard wheelchair and require continuous personnel support and monitoring and, as a result, have no independent mobility and consequently no freedom.

According to [101] the vast majority of people employing powered wheelchairs rely on joystick, sip-and-puff, chin, or head control interfaces. Very sophisticated control technologies such as eye gaze or tongue pad interfaces are employed by fewer than five percent of power wheelchair users. The indication is that individuals with severe disabilities which compromise respiratory drive and/or limit the dexterity of the head and hands have few options for steering a powered wheelchair and a NEPWAK equipped wheelchair might be able to address some of the mobility needs of these individuals.

Interviews with care providers and those who worked with disabled individuals generally mentioned that while NEPWAK would be suited to "closed environments" and indoor settings such as shopping malls, they doubted it could be used safely in outdoor environments.

On the positive side NEPWAK would allow people to show independence and a willingness to embrace technology. In regards to the positive viewpoints on NEPWAK, one interviewee made a forceful case that the chair will allow those

with a severely limiting disability opportunity to go to different destinations that they wouldn't be otherwise able to reach. She stated that hesitancy and concerns about safety could be overcome through the use of demonstrations, workshops and/or weekend training sessions. The training and the assessment period that a blind person goes through when first using a seeing-eye dog was given as an example. On a concluding note, despite the need for continuing work before the system could be commercially available, this research resulted in many successful steps towards the goal of a deliverable system that might one day help people in a meaningful way.

Appendix A: PCM-9575 PC-104 Single Board Computer

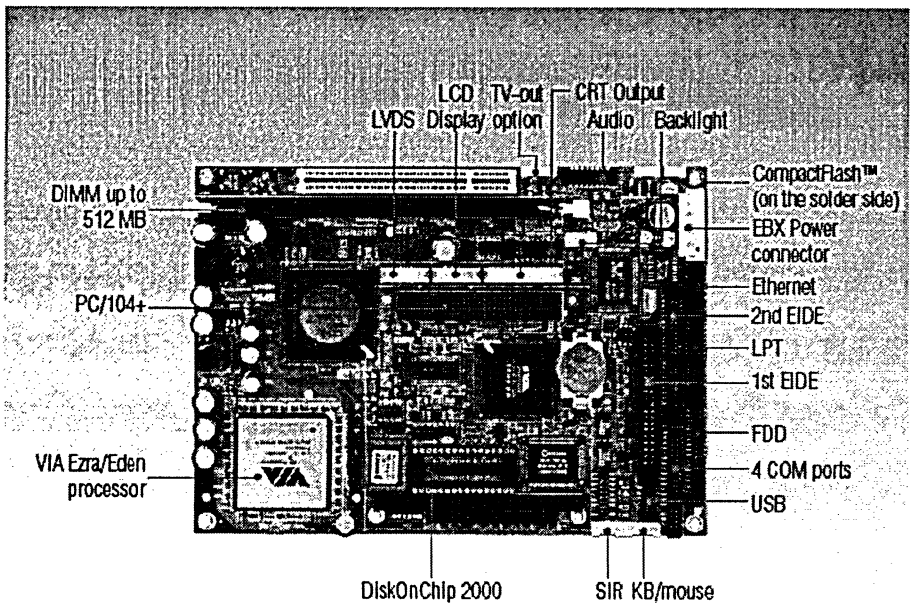


Figure A.1: PCM-9575 PC104 module

The PCM-9575 is a new EBX form factor 5.25" single board computer (SBC) with an onboard new VIA Embedded low power Eden 667MHz, or Eden 400MHz processor. The VIA Eden processor uses advanced 0.13μ CMOS technology with 128KB L1 cache memory and 64KB L2 cache memory on-die. This board can operate without a fan at temperatures up to 60° C (140° F) and typically consumes under 14 Watts while supporting numerous peripherals. This SBC includes a 4X AGP controller, a PCI audio interface, a PCI Ethernet interface, and 2 channel LVDS interface. Its design is based on the EBX form factor that supports the PC/104+ interface for ISA/PCI module upgrades. Other on-board features include a PCI slot, an LPT, 2 USBs, IrDA and 4 serial ports: three RS-

232s, and one RS-232/422/485. The SSD solution supports both DiskOnChip® 2000 and CompactFlash™ cards.

This product uses a VIA Twister™ chip with Integrated Savage4™ 2D/ 3D/Video Accelerator and supports 4X AGP VGA/LCD interface and up to 32 MB frame buffer using system memory. The board is effective for use as a mini-server or gateway device, through its ability to add more ethernet ports through its fast PC/104+ socket. The PCM-9575's powerful, fanless processor choices and solid system chipset make it a perfect core technology for medical equipment and other long life applications.

A.1: Features

- Embedded low power VIA 400 MHz to 1 GHz processor
- Applied EBX form factor standard and supports PC/104+ bus
- Fanless operation at 60° C (PCM-9575F-J & PCM-9575F-M only)
- 133MHz FSB and 4X AGP graphics for high performance applications

A.2: Specifications

A.1.1 Standard SBC Functions

- **CPU:** Embedded VIA low power Ezra/Eden processor, 128KB L1 cache memory on die

- Eden-400 MHz (PCM-9575F-J)
- Eden-667 MHz (PCM-9575F-M)
- C3 1 GHz (PCM-9575F-S)

- BIOS: Award 256 KB Flash memory
- System memory: One DIMM socket, 64 MB up to 512 MB SDRAM PC133
- 2nd cache memory: 64KB on the Ezra/Eden processor
- Enhanced IDE interface: Two channels supports up to four EIDE devices. BIOS auto-detect, PIO Mode 3 or Mode 4, UDMA33 transfer. Primary IDE supports up to UDMA66/100 mode.
- FDD interface: Supports up to two FDDs
- Serial ports: Four serial RS-232 ports - COM1, 3, 4: RS-232, COM2: RS-232/422/485
- Parallel port: Parallel port supports SPP/EPP/ECP mode
- Infrared port: Shared with COM4. Transfer rates up to 115Kbps
- Keyboard/mouse connector: Supports standard PC/AT keyboard and a PS/2 mouse
- Power management: Supports power saving modes including Normal/Standby/Suspend modes. APM 1.2 compliant
- Watchdog timer: 62 level timer intervals
- USB: Two universal serial bus ports (4 USB ports optional)
- Expansion: 1 PCI slot, PC/104+ connector for ISA and PCI control board

A.1.2 VGA/Flat-Panel Interface

- Chipset: VIA Twister™ chip with integrated Savage4™ 2D/3D/Video Accelerator
- Frame buffer: Supports 8/16/32MB frame buffer with system memory
- Interface: 4X AGP VGA/LCD interface, Support for 9, 12, 15, 18, 24, 36 bit TFT and optional 16- or 24-bit DSTN panel
- Display mode:
    - CRT Modes: 1280 x 1024@16bpp (60Hz), 1024 x 768@16bpp (85Hz)
    - LCD/Simultaneous Modes: 1280 x 1024@16bpp (60Hz), 1024 x 768@16bpp (60Hz)
- LVDS: Supports 2 Channel (2 x 18bit) LVDS interface

A.1.3 Ethernet Interface

- Chipset: RTL 8139
- Ethernet interface: IEEE 802.3u 100BASE-T Fast Ethernet compatible
- I/O address switchless setting
- Built-in boot ROM

A.1.4 Audio Function

- Chipset: VIA 82C686
- Audio controller: AC97 ver. 2.0 compliant interface
- Audio interface: Mic in, Line in, CD audio in, Line out, Speaker L and R

A.1.5 Solid State Disk

- Supports one 50-pin socket for CFC type I/II
- Supports M-Systems DOC® 2000

A.1.6 Mechanical and Environmental

- Power requirements:
  - Max: 4.5A @ +5V
  - Typical: 3.1A@+5V(Eden 400MHz)
- Operating temperature: 32 to 140°F (0 to 60°C)
- Dimensions (L x W): EBX form factor, 8.0" x 5.75" (203mm x 146 mm)
- Weight: 0.85 kg (weight of total package)

A.1.7 Operating System Compatibility

- Linux & RTAI Real-Time Linux
- Microsoft Windows XP / XPE
- Microsoft Windows CE /CE.net
- Microsoft Windows NT / NTE
- Microsoft MS-DOS 6.22 & RomDos 6.22
- Wind River VxWorks
- QNX Neutrino RTOS

Appendix B: PIC16F876 Microcontroller

Figure B.1: PIC16F876 Microcontroller

This powerful (200 nanosecond instruction execution) yet easy-to-program (only 35 single word instructions) CMOS FLASH-based 8-bit microcontroller packs Microchip's powerful PIC® architecture into an 28-pin package and is upwards compatible with the PIC16C5X, PIC12CXXX and PIC16C7X devices. PIC16F876 features 256 bytes of EEPROM data memory, self programming, an ICD, 5 channels of 10-bit Analog-to-Digital (A/D) converter, 2 additional timers, 2 capture/compare/PWM functions, the synchronous serial port can be configured as either 3-wire Serial Peripheral Interface (SPI™) or the 2-wire Inter-Integrated Circuit (I^2C™) bus and a Universal Asynchronous Receiver Transmitter (USART). All of these features make it ideal for more advanced level A/D applications in automotive, industrial, appliances and consumer applications. The table B.1 summarizes the specifications:

Data Ram	Speed MHz	I/O Ports	ADC 10-bits	Serial I/O	PWM	Timers	Brown Out	ICSP
368	20	22	5	USART, I^2C, SPI	2	3+WDT	True	True

Table 1: PIC16F876 Specifications

Appendix C: Sharp GP2D12 Proximity Sensor

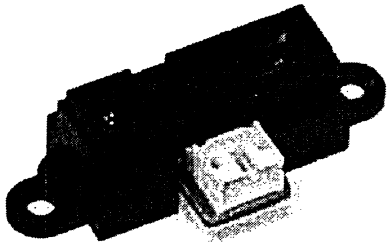


Figure C.1: Sharp GP2D12 Proximity Sensor

This sensor takes a continuous distance reading and reports the distance as an analog voltage with a distance range of 10cm (~4") to 80cm (~30"). The interface is 3-wire with power, ground and the output voltage and requires a JST 3-pin connector. The GP2D12 sensor works by employing the triangulation principle. An infrared diode emits a modulated beam, this beam hits an object and a portion of the beam is reflected back to the receiver optics to strike the Position Sensing Device (PSD). The reflected beam passes through a lens arrangement so that, depending upon the distance of an object; it hits a specific area on the PSD. Depending on where it hits on the PSD generates a voltage that can be used as a measure of the distance. The unit is highly resistant to ambient light and nearly impervious to variations in different types of surface reflectivity.

C.1: Specifications

C.1.1 Absolute Max Ratings

Parameter	Symbol	Rating	Unit	Remarks
Supply Voltage	V_{CC}	-0.3 to +7	V	
Output Terminal Voltage	V_O	-0.3 to V_{CC}+0.3	V	
Operating Tempurature	T_{opr}	-10 to +60	°C	
Storage Tempurature	T_{stg}	-40 to +70	°C	

C.1.2 Operating Supply Voltag

Parameter	Symbol	Rating	Unit	Remark
Operating Supply Voltage	V_{CC}	4.5 to 5.5	V	

C.1.3 Electro-Optical Characteristics

Parameter	Symbol	Conditions	Min.	Typ.	Max.	Unit
Measuring distance range	delta L	*1	10	-	80	cm
Output Terminal Voltage	V_O	L = 80 cm *1	0.25	0.4	0.55	V
Output voltage difference	delta V_O	Output change at L change (80 cm -> 10 cm) *1	1.75	2.0	2.25	V
Average supply current	I_{cc}	L = 80 cm, *1	-	33	50	mA

L: Distance to reflected object.

*1 Using reflected object: White paper (Made by Kodak Co. Ltd. grey cards R-27, white face, reflective ratio: 90%)

Appendix D: NEPWAK Feedback Questionnaire

1. Are the controls easy to understand?

   (Hard to understand) **1** **2** **3** **4** **5** **(Easy to understand)**

   Comments: _____

   _____

2. Do the controls provide good action feedback from your input?

   (Bad feedback) **1** **2** **3** **4** **5** **(Good feedback)**

   Comments: _____

   _____

3. Do the controls provide enough freedom of movements and choices for you to control the wheelchair?

   (Not enough choices) **1** **2** **3** **4** **5** **(Adequate choices)**

   Comments: _____

   _____

4. Does the video feedback provide adequate amount of information for controlling the wheelchair?

   (Not enough info.) **1** **2** **3** **4** **5** **(Adequate info.)**

   Comments: _____

   _____

5. How would you rate the quality of the video feedback?

   (Poor) **1** **2** **3** **4** **5** **(Excellent)**

   Comments: _____

   _____

6. How would you rate the quality of the audio feedback?

   (Poor) **1** **2** **3** **4** **5** **(Excellent)**

   Comments: _____

   _____

7. Do you see a potential for NEPWAK to be used in Health care facilities and homes for remote care?

Comments:_____

8. How would you rate the overall NEPWAK system?

(Bad initiative) 1 2 3 4 5 6 7 8 9 10 (Good initiative)

9. Please provide any further comments/ideas for improving NEPWAK

-_____

Optional

Name: _____

Occupation: _____

Contact Information:

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