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Computer Simulations of Personal Robots

by

Jun Wang

A THESIS
submitted to the School of Graduate Studies and Research
in partial fulfillment of the requirements
for the degree

Master of Applied Science
in
Electrical Engineering

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ABSTRACT

It has been recognized for some time that persons with severe physical disabilities could benefit greatly if they had a personal robot under their control. Such kind of robots has been available for several years, but the acceptence by disabled persons has been very slow. One of the reasons is a concern for safety. If a robot arm is strong enough to bring food to a person's mouth, then it could do severe personal injury to the eyes or teeth in the event of an electronic or mechanical failure.

In this thesis, a new approach of investigating a personal robot will be presented. A three-dimensional computer simulation of a personal robot will be described. It is completly under the control of the user. This simulation system has many advantages over testing an actual model, since it enables almost any type of personal robot and any type of control strategy to be investigated. This system can be used by researchers to investigate control algorithms for a personal robot. It can also be used by disabled persons so that they can get familiar with the robot as well as the control strategy before they use or purchase the actual model. Currently, this simulation is used to investigate a control strategy called "Modified Extended Physiological Proprioception".

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Chapter 1

Introduction

This chapter will first briefly describe the motivation of our research. After that, we will state our research objective and procedures. Finally, we will give an outline of the thesis.

1.1 Motivation

There are significant numbers of persons whose physical impairments are so severe that they are unable to effectively interact with their environment without the assistance of other people. Offering such persons a means of learning, creating independently and also controlling their own environments, would reduce the cost of their health care and it would also allow them to contribute to society in many ways. Their contributions could include being gainfully employed and paying taxes. Robots are among the more important devices which can help these severely disabled persons to reach the required level of independence. The aim of research into personal robots is, therefore, to give those people physical control of their environment without requiring continuous assistance from other people.

1.2 The Use of Robots by Severely Disabled Persons

Most severely disabled persons want to be as independent as possible in: activities of daily living, recreation, and in employment. Persons who do not have the control of their arms as a result of their illness or injuries, could perform vital manipulative tasks with the help of a personal robot. Since the early 1980s, many personal robots have been built, tested, and evaluated in North America and in Europe, but for several reasons, their commercial acceptance has been slow. One of the reasons is concern for the safety of the user. Close interaction between a robot and a disabled user can be dangerous because many existing personal robots are controlled in an open loop manner and cannot themselves detect and prevent potential collisions with the environment, with patients, or with attendants. For example, if a robot arm is strong enough to bring food to a person's mouth, then it could do severe personal injury to the eyes or teeth in the event of an electronic or a mechanical failure.

To improve the control of a personal robot, we have turned our attention to a control strategy called Extended Physiological Proprioception (EPP) which was originally introduced by Dr D. C. Simpson for the control of upper-extremity prostheses [1-2]. The term EPP is commonly used in the rehabilitation area. It implies that the body's natural position proprioception is extented outside the body to artificial devices (e.g. prosthese or robots). This is achieved by establishing a direct relationship (or relationships) between the positions of intact joints and the position in space of the artificial device. Once the subject learns the relationship (or relationships), the natural position proprioception of the intact joints can be extended to include the position of the artificial device.

In a previous research project in this department on externally powered upper-extremity prostheses, a modified form of EPP was demonstrated successfully [3-5]. This modified EPP improves the control of a multi–functional prosthesis by supplying the amputee with position proprioceptive feedback of the terminal device for a number of input-output relationships (or linkages). We believe that this control strategy can also be used in the control of a personal robot and that it will significantly improve the safety of a disabled user.

At this early stage in the development of our robot control algorithm, computer simulations of the complete system have the following advantages over actual models.

- Accurate simulation of system dynamics and easy implementation of changes to actuators, dimensions, materials, etc.
- Precise measurement of accomplishments, compilation of results, and performance of statistical analysis.
- Elimination of risks to subjects or investigators.

- Less expensive than constructing an actual model or prototype.

1.3 Research Objective

While the long-term objective of the research in this area is to investigate the control strategy called Extended Physiological proprioception (EPP), the work reported in this thesis is an investigation of the use of computer simulations instead of actual models for accurate measurement of performance. The main questions to be answered are:

- Can we provide an experimental subject with a realistic three-dimensional simulation of a personal robot or other similar device?
- Can we realistically simulate the motor characteristics and dynamics and also the dynamics of motion of the robot?
- Can we adjust the dynamics to simulate system changes, such as different motors or different loads?
- Can we simulate different input-output relationships (or linkages)?

In the future, the simulation could be used to answer questions such as the following:

- Can the principles of EPP be used in the control of a personal robot in addition to a prosthesis?
- Can the idea of EPP be modified by replacing the fixed 1:1 relationship between input and output by preprogrammed selectable linkages?

- Can the investigation of EPP be made by using computer simulation instead of an actual model?

1.4 Basic Approach to the Research

The first step was to establish a computer simulation of a commercial personal robot. We chose the Neil Squire Robotic Arm for our simulation because it is a very well designed robot system for disabled persons.

The second step was to select the proper human interface to control our three-dimensional simulator. We selected head movement as our main input modality.

The third step was to establish the preprogramed linkages, and to specify the tasks.

The final step was to establish a method for measuring error and time and also a method of controlling an experiment, including the control of targets.

1.5 Organization of the Thesis

This thesis is organized as follows:

In Chapter 2, we will review the application and current status of robot systems for disabled persons. We will also review the human interface and the control strategies that are used in these robot systems and also the problems encountered to date.

In Chapter 3, we will present the basic control strategy called Extended Physiological Propriception (EPP). Modifications of EPP for the control of externally powered prostheses and robotic systems will also be discussed.

In Chapter 4, we will present the complete simulation system. The advantage of computer simulation over an actual system will be discussed. The specific system under study (i.e the Neil Squire Robot) will be described. The hardware and software of our simulation system will be discussed in detail.

In Chapter 5, we will summarize the results of the study. The suggestions for further research will also be given in this chapter.

Chapter 2

The Development of Personal Robots

In this chapter, the development and the current status of personal robots will be reviewed. Emphasis will be placed on the control interface. The intent of this review is to point out some of the applications in the rehabilitation area where robots are currently being used or tested.

2.1 The Development

The applications of robots in health care have been approached from many different directions such as surgical robots, laboratory robots, and personal robots [6]. An area with many important applications for personal robots is rehabilitation. Rehabilitation is the restoration of normal form and function after injury or illness [7]. This area is specially important because the potential benefits to persons with disabilities are very great.

The largest cost of disability is not medical care but maintenance, attendant care, nursing home care expenses, the loss of productivity because of the inability to work, and the lost wages of family members who have to take time off from their jobs in order to help. It is interesting to note that in the United States of America for 1980, over three thousand times as much money was spent on personnel and equipment used in caring for the disabled than was spent on research and development related to technology which would allow the disabled to care for themselves ($ 210 billion versus $ 66 million) [8]. Money spent on research and development for assistive devices is economically beneficial to society ($ 1.00 spent on research and development returns $ 11.00 in cost benefits to society) [9]. These reports illustrate the need for research in areas such as personal robot technology.

Robots offer disabled persons the opportunity of enhancing the quality of life by increasing their functional independence in society and by decreasing medical costs. Unlike its industrial counterparts, this kind of robot is not designed to perform repetitive tasks. Instead, the personal robot must be able to perform various tasks in unstructured environments.

A disabled person can benefit from personal robots in the following specific areas: in activities of daily living, such as preparing food and eating; in personal clerical tasks, such as operating a telephone or a calculator; in vocational tasks, such as computer programming or secretarial work; and in recreational tasks, such as controlling electronic games, playing chess, or painting.

According to Leblanc and Lefifer [10], a personal robot aid should include certain basic features:

- It must have one or more manipulative arms that can be moved about the environment and are capable of bringing an end effector (a hand) to any position and orientation within a working volume.
- The end effectors must have tactile sensors that provide the user with functional information about object location and grasp quality.
- The arm and hand must be controlled by one or more computers to perform complex tasks upon receiving specific commands.
- The user needs one or more input interfaces for complete system control.
- To have comprehensive awareness of the robot's actions and knowledge, the user must have one or more feedback pathways.

The work on personal robotic manipulation aids began in the late '60s and early '70s. Researchers at the University of Heidelberg, Germany were the first to use an industrial manipulator to aid the disabled [11]. The electromechanical arm had five degrees of freedom plus grasp. It was about 1.3 times human scale and occupied a fixed location within a highly structured work station. A minicomputer performed cylindrical coordinate transformations, stored intermediate points, and integrated the use of special environment adaptations (a modified telephone, special typewriter, custom mouth-stick keyboard, and a three degrees of freedom mouth manipulandum). The user initiated and controlled all the motions of the manipulator. Since then, many different personal robots have been built, tested,

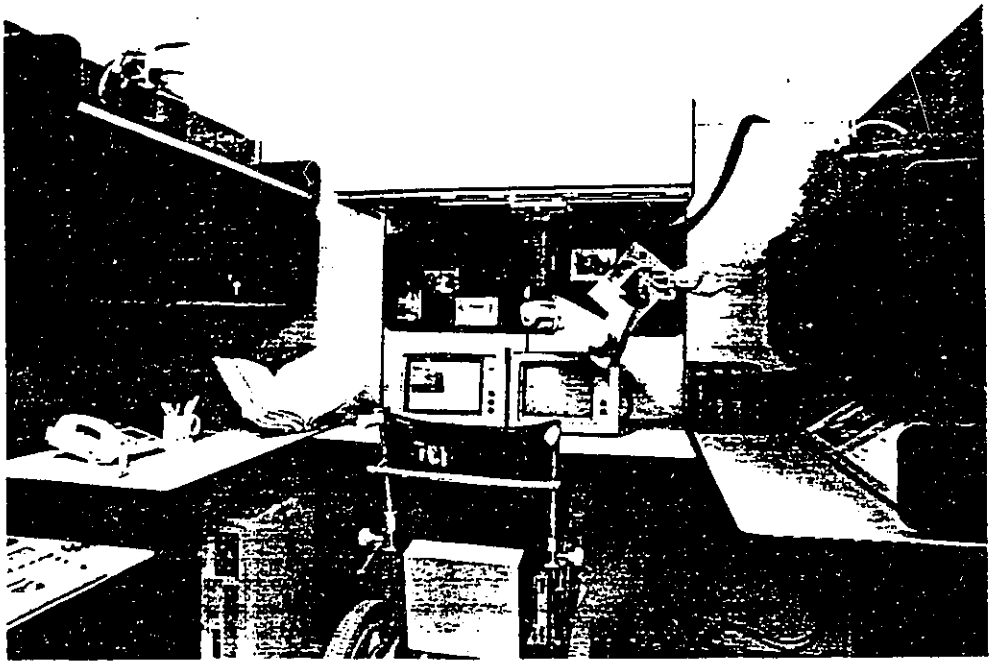

Figure 2.1: The VA/Stanford DeVAR System

and evaluated in North America and in Europe. The most noteworthy among them are the Stanford Robotic Workstation [12], the Johns Hopkins Robotic Arm Work Station [13], and the Manus system of the Netherlands [14].

The VA/Stanford group began in 1980 with a feasibility study of a desktop voice-controlled robot. Currently, the project is concentrating on two areas: clinical and vocational assessment of the desktop system (DeVAR) [Figure 2.1], and technological development of an omnidirectional mobile robot.

The DeVAR system incorporates an industrial manipulator (Unimation PUMA-260), a standard microprocessor based voice-command unit, a synthesized voice response, a smart sensate hand, a non-contact head control unit, and a mixed mode hierarchical control software running in five independent microcomputers. The six degrees of freedom PUMA-260 is driven by DC torque motors with incremental optical encoders in an all-digital position servo.

The DeVAR has evolved from a series of prototypes. The researchers have been evaluating the system's performance with activities of daily living and vocational needs. Examples of daily living tasks include preparing a meal and brushing teeth. Vocational aids concentrate on the needs of a disabled programmer. Examples of tasks include: printer-output management, textbook and manual handling, and mail manipulation.

The VA/Stanford Mobile Robot consists of not only a PUMA manipulator, but also a vehicle which can move around. It contains speech recognition and voice synthesis units for the user and the robot's controller. An interface program presents status information on monitor screens and sends the spoken commands to the robot. Because the working envelope of mobile robots is more complicated than the desktop model, a set of sensor subsystems have been defined to give the mobile manipulator the necessary autonomy and safety while operating under the supervisory control of a disabled person.

The JHU Robotic Arm Work station has been developed by researchers at Johns Hopkins University for high level (shoulder level) quadriplegics. The robot arm is a six degrees of freedom device which is controlled by a low cost computer

(6809 microprocessor). The input mode to the robot is chin motion. The concept of a workstation is based on placing components in fixed locations on the work table such that the robot arm can use manual step by step motion or prestored computer controlled motion trajectories to carry out the desired functions. The system not only provides direct control of any single axis of freedom within its six degrees of freedom motion, it also enables users to select one of many prestored trajectories to accomplish a specific task. Such tasks include: self-feeding, handling a variety of reading materials, the use of a telephone, and the use of a computer. An important tool used in conjunction with the robot arm is a mouthstick. Manipulative functions such as putting a magazine in place for reading are accomplished by the robot, while page turning is often accomplished by use of a mouthstick.

In Europe, several projects have been developed which include: the French Spartacus project and the Dutch Manus project. The Manus project is aimed at the development of a reasonably priced wheelchair mounted manipulator with a modular computer control structure, usable by persons with severe disabilities in all four limbs. Its articulated arm has eight degrees of freedom, including grasping. A wheelchair mounting kit is used to adapt the system to different types of wheelchairs. Individually selectable controls and reconfigurable microcomputer-assisted procedures are used to control both gripper and wheelchair movements. A limited number of preprogramming and replay features are offered to speed up or facilitate certain tasks, but the operation is always closely controlled by the operator. A display mounted near the gripper and a sound signal will provide an elementary feedback to the user to enable him to select control modes and to communicate various message to him. Headset control is one of the control interfaces being used. It can be used to control both manipulator and wheelchair movements.

Personal robot development in Canada has been very modest. Several pilot projects have been developed by the Neil Squire Foundation [15], the University of Toronto, and the University of Saskatchewan.

The Neil Squire Robot Arm [Figure 2.2] has been under development since 1983. It was developed as a manipulative appliance for people with severe physical disabilities. Currently, the robot system is commercially manufactured through Regenesis Development Corp. The system is a six degrees of freedom robot. It is powered by 24 volt D.C. motors and is controlled by a digital P.I.D. controller. It is user programmable and easy to use. This robot is intended to assist the disabled in activities of work and daily living. In a vocational setting, the arm could be used to manipulate objects such as books, paper and computer diskettes. In activities of daily living, the robot could assist in feeding, toiletry and recreational routines. Safety features strive to enable the user to work safely within the robot's envelope or working environment. These features combine a 16 millisecond power shutdown watch-dog, individual torque levels, independent C.P.U. on-line monitoring, power up self test, C.P.U. motor shut down control and a panic stop.

In order to illustrate the varieties of robots used in health care, one special application for a robot will be mentioned. This is the use of a robot system and

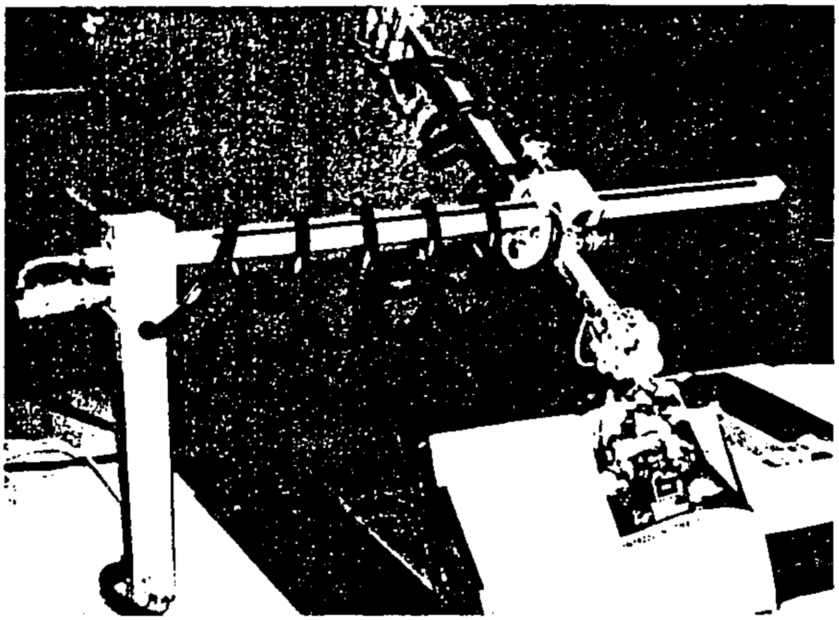

Figure 2.2: The Neil Squire Robot System

sensing devices to help the blind. They can be used to help with the problem of navigation. One of the recent robotic aids for the blind is the Japanese MELDOG project [16]. This robot is designed to replicate the functions of a guide dog. It can be programmed with "land mark" information from a city and has the capability of guiding its owner to a desired destination.

According to Leblanc and Leifer [10], three conditions must be met by a robotic aid before it can be an economically feasible partial substitute for human care:

- Its manipulative capability must be sufficiently good to make it an attractive alternative to some classes of human assistance.

- It must be reliable enough so that the user and attendants will be encouraged to use it.
- Savings (and/or earnings) derived from using the robotic aid must pay for its initial and maintenance costs.

2.2 Interface and Control Algorithm

Unlike the normal human operator, some disabled persons have very limited use (or no use at all) of their hands to operate the controls necessary to specify the movement of the robot. For these reasons, major work is required in the development of appropriate man-machine interfaces. This aspect of man-machine communication is a major factor in the success or the failure of applying robotic technology in the development of assistive devices for severely disabled persons.

There are two distinct types of interaction between the robot and user: continuous and momentary [17]. For a disabled person, tasks requiring a series of manipulations, such as driving a vehicle, preparing a meal, or setting up books and notes for studying, would be performed quickly and efficiently if the control of the robot was an extension of the operator's remaining voluntary movement. In this type of control, the user is able to respond quickly, accurately and reliably. On the other hand, some tasks such as turning the light on or off or initiating a preprogrammed set of actions require only brief attention from the user. This kind of control is momentary.

For physiologically normal persons, the principal media to manipulate the environment are the hands. In performing both continuous and momentary control functions, the hands serve as versatile physical and sensory extensions of the mind. For disabled persons, possible remaining continuous control inputs include: head movement, eye movement, chin displacement, jaw displacement, torque displacement, respiratory pressure patterns, vocalization patterns, electromyographic activity, and electroencephalographic activity. Possible momentary inputs include: voice commands, keyboards, and switches. Although personal robots may have the mechanical capabilities to carry out a variety of tasks, the tasks actually performed by these devices are likely to be chosen based on the type of control (interface) used and on the user's requirements. Control should be natural, or intuitive, and the system should be highly responsive to that control. Otherwise, the mental effort expended in the control of the device in a continuously interactive manner would overshadow the benefits of the tasks performed by the device. If the control interface of a remote manipulator or robot could provide the physically disabled person with a natural extension of intact physical and sensory abilities, this person will be likely to use the device interactively in novel situations and in an unstructured environment [18-19].

The control interfaces used in existing personal robots vary a lot. They depend on the specific system designed, the tasks specified, and the remaining functions of the disabled user.

In the Stanford Robotic Project, a robot is controlled by spoken commands, a joystick stored program, and rudimentary hand sensors. Speech input is the primary communication medium. Their speech recognition systems can recognize and analyze commands given in the form of simple English sentences. "Pick up the cup", for example, would be translated into appropriate low-level robot-specific commands. The user would be informed about the command passed on to the robot controller through a DEC Dectalk unit and a visual display. Several sensory approaches were also used to alleviate the burden of a user who relies on visual perception to guide the robot arm. The proximity sensors on the hand deal with objects at distances of 1-2 centimeters. This is for object detection during grasping and collision avoidance during large movements. The arm is equipped with a force sensor at the wrist of facilitate tasks such as placing a grasped object on a table and operating a push button.

For the John Hopkins Robot Arm system, many control input methods were examined as possible input modes to the system. Safety of operation and ease of user control were important goals for the input devices. Chin motion input was selected because of its positive control and good resolution capability. The chin motion sensor may be a dual purpose controller or it may be a stand-alone device mounted on the workstation. Small up and down chin motions provide proportional control of selection of individual joint motion or prestored motion sequences. A single pulse generated by a slight rocking fore and aft movement causes an event to start or stop. For those individuals who cannot operate a chin controller, a sip and puff controller is available. Some manipulative functions are accomplished with the aid of a mouthstick.

For the Neil Square Robot Arm, a variety of user input control options are available which include: voice, direct keyboard access, expanded keyboard, and single or dual switch morse code or row scanning. The user interface, which works with an IBM compatible personal computer, is menu driven. Commands are displayed on the screen and are selected by moving the cursor to the desired command and entering a carriage return. This interface is used to record, edit and playback tasks, move selected joints in real-time, and move the robot in conjunction with a master/slave control.

Chapter 3

Control Strategy

Our computer simulation can be used to investigate the various control strategies of a personal robot. At present, the control algorithm we are studying is called Extended Physiological Proprioception (EPP). Therefore, in this chapter we will briefly discuss the concept of EPP.

3.1 Basic Idea of EPP

The concept of Extended Physiological Proprioception (EPP) was originally proposed for the control of prostheses by Simpson [1-2]. Thus before outlining EPP to control our robot, we will give a brief overview of control strategies used in the control of prostheses.

A prosthesis is an artificial device fitted on an amputee to replace some of the limbs that he/she has lost. For a powered prosthesis, the amputee has to send control commands to the prosthesis requesting the desired functions. For the past twenty years, the control of externally powered prostheses has been a concern of researchers. Several control methods have been investigated. Among the control methods, using the myoelectric signal (EMG) from biological activities appear to be the most elegant.

Conceptually, myoelectric control of a prosthesis is very straightforward [20]. The small, electrical potentials from selected muscles are amplified and directed to a controller that drives the prosthesis. The myoelectric signal is usually obtained from electrodes placed on the skin over one or more active muscles. A simple example of the myoelectric control involves using the electrical signals from biceps muscles to control the opening of an artificial hand, and using the electrical signal from triceps muscles to control the closing of an artificial hand.

An advantage of EMG control is the natural synergy that matches the neuromuscular effort with the corresponding limb response. A major disadvantage of myoelectric control is that it gives the user little feedback about the position of the artificial joint which is controlled by the myoelectric signal. This control relies highly on direct visual feedback. One reason is due to the fact that EMG is an efferent (and open-loop) signal. It is capable of providing communication from man to prosthesis but not vice versa. The second reason for the necessity of visual feedback is that the activity of the muscles is represented poorly at the conscious levels in the central nervous system. Thus an amputee using an EMG controlled prosthesis would be poorly aware of what the machine was doing and hence would have to rely heavily on direct visual observation of the prosthesis.

As the number of degrees of freedom of the prosthesis increases, a larger amount of user concentration is required. This is very undesirable since the main activity of the amputee should not be the control of the prosthesis. Rather, he should be able to perform other activities such as talking or thinking while he is performing a task with his artificial arm. Thus, the control of the prosthesis has to be subconscious in nature as is the case in the control of the natural arm.

Efforts to provide sensory feedback to amputees by means of externally generated stimuli have included electric stimulation [21] and vibration feedback [22]. While these feedback systems have some use in providing force feedback, they have proved to be equally unsuitable for position feedback. Thus the EMG controlled prosthesis must be considered an open-loop system since no satisfactory position feedback has been found for an amputee. The lack of such proprioceptive information, and the dependence on visual feedback, leads to the rejection of their prostheses by many of the amputees. However, other techniques which are less elegant but more promising have been suggested.

The concept of Extended Physiological Proprioception (EPP) implies that the manner in which an artificial arm is controlled and used can provide position proprioception similar to normal movement. It is based on the use of residual joints with intact position proprioception to provide the amputee with an inferred knowledge of the position of the artificial arm. The knowledge of the position of the joint can therefore be "extended" to the knowledge of the position of the artificial arm if the relationship is learned by the user. So the position of the artificial arm is always directly related to the position of an intact part of the body. All EPP systems rely on the inherent awareness of the position of intact joints to provide position proprioception.

The cane of a blind person and the racquet of a tennis player are good examples of EPP. As Doubler and Childress [23] say: " The manner in which a blind person uses a cane as a mobility aid is an excellent illustration of this concept. Information about the environment is coded in proprioceptive sensations arising in the extremity supporting the cane. Although transmitted by the cane, these sensations do not pertain only to the nature of the cane, but rather serve to describe aspects of the nature of the environment. Thus the cane serves as an extension of the blind person's existence, shifting outward the point at which contact is made with objects external to the person's being."

By a certain amount of training, a tennis player can learn to associate his body joints with the position of the artificial extension (i.e. the racquet). Similarly, an amputee can learn to associate the position of the prosthesis with the position of the controlling joint of the body.

3.2 Modified EPP

One problem with existing prosthesis systems is that the complexity of operation increases with increasing functionality. If two or more joints of the prosthesis are involved in the control, a lot of concentration is required for normal coordinated control. By using linked motions (linkages), i.e. one natural joint motion resulting in the motion of two or more prosthetic joints, the amputee would be relieved from the burden of coordinating the different prosthetic joints. But a prosthesis system with a fixed linkage would limit the amputee's ability to perform more than a few tasks, because its motion would be constrained by the single input-output relationship.

Gibbons and O'Riain [5] have suggested a major modification to conventional EPP with a design for an externally-powered prosthesis. By using the microprocessor, the linkage could be pre-defined and be selectable by the amputee. The selectability of various linkages overcomes the difficulty imposed by conventional linked motion prostheses, where the amputee is easily able to perform a few tasks with his prosthesis while he finds it impossible to perform others. Using the approach of Gibbons and O'Riain, the amputee will be able to choose the proper linkage for the task he wishes to perform.

For the above-elbow prosthesis, Gibbons and O'Riain decided to use the shoulder joint as the controlling input. This choice of the shoulder position as the input signal was based on the recognition of the fact that many manipulative tasks involve a coordination of the shoulder, elbow, and wrist movements. Thus, the use of the shoulder joint will help to make the prosthesis movements resemble natural arm movements. For the same shoulder position, a different choice of linkage will result in a different positioning of the prosthesis.

It is expected that the amputee will be able to learn the various linkages that are available to him after a training period. By learning those linkages which are essentially the input-output relationships of the prosthesis, he will be able to associate his shoulder joint with the position of the artificial arm. Therefore he will have excellent proprioceptive feedback.

The artificial arm joints will be controlled as defined by the pre-programmed linkages. Therefore, simultaneous coordinated motion with proprioceptive feedback will be achieved.

The prosthesis designed by Gibbons and O'Riain was shown to have many useful features. The following chapter will show that many of the features of the prosthesis design can be adapted for our computer simulation.

Chapter 4

Computer Simulation

In this chapter, the complete computer simulation will be discussed. The discussion includes the advantages of computer simulation over using an actual model, the system being simulated, the simulation system, the simulation software, the linkages, the dynamic system and our learning protocol for EPP.

4.1 Advantages of Computer Simulation

It has been recognized for some time that persons with severe physical disabilities could benefit greatly if they had a personal robot under their control for tasks such as: feeding, self-care tasks, retrieving objects throughout the room, opening doors, answering the telephone, etc.

While robots were shown to perform very effectively in science-fiction movies, the resulting high expectations among the public have not yet been met. Some problems with current robots are summarized by the following:

- Robots are difficult to control, especially if the operator is severely disabled.
- Robots are powerful enough to cause severe injury to the user (for example by stricking the eyes or the teeth). If they were not this powerful, they could not perform many useful tasks.
- The mandatory industrial precautions to separate the robot from the operator with a metal screen, will not work for personal robots which perform many tasks requiring direct contact with the user's face (e.g. for feeding, shaving, etc.).

The initial experiments on personal robots were done using actual prototype units. However, major problems were encountered with this approach, including the following:

- Getting accurate measures of performance was very difficult, involving the use of stop-watches and tape measures. The procedures took some time and the results were not very accurate.
- If changes were needed to the robot under study, expensive and time-consuming hardware changes had to be made.
- Statistical analysis of the results also required that the data be entered a second time into our analysis program.
- Errors in the control algorithms, or non-optimum control strategies in our prototypes, could cause severe injuries to the experimental subjects prior to

all programming errors being detected and corrected

On the basis of their earlier experiences, O'Riain and Gibbons have decided that the best strategy for our University-based studies is to replace actual prototype models with high-quality computer simulations [24-25]. The computer simulations have the following benefits: they are risk-free; the parameters of the system can be modified quite easily; and both the research protocol and results can be managed very efficiently by the computer system.

O'Riain and Gibbons decided to use Neil Squire Robot for the simulation model. The reason they selected the Neil Squire Robot is that it is an advanced personal robot and that it is made in Canada

4.2 The System Being Simulated

The Neil Squire robot has been available since 1983. It was designed specifically for users with disabilities. It is composed of a vertical stand, a horizontal track which is called track 1, another movable track crossing track 1 at right angles which is called track 2, and a gripper. Track 2 can slide on the track 1. Track 1 can rotate around its longitudinal axis causing track 2 to describe an arc in the workspace. The gripper can perform the motion of roll, yaw and pitch. Therefore, this robot has six degrees of freedom. Figure 4.1 shows the isometric view of the robot and Figure 4.2 shows its work envelope[1].

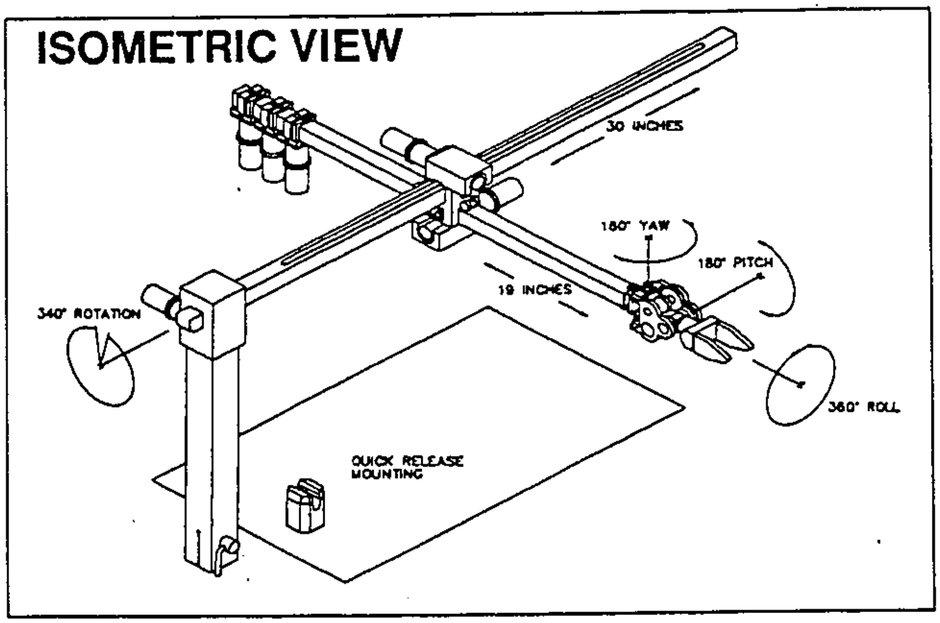

Figure 4.1: Isometric View of Neil Squire Robot

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[1] These figures are taken from the product literature of Neil Squire Robot.

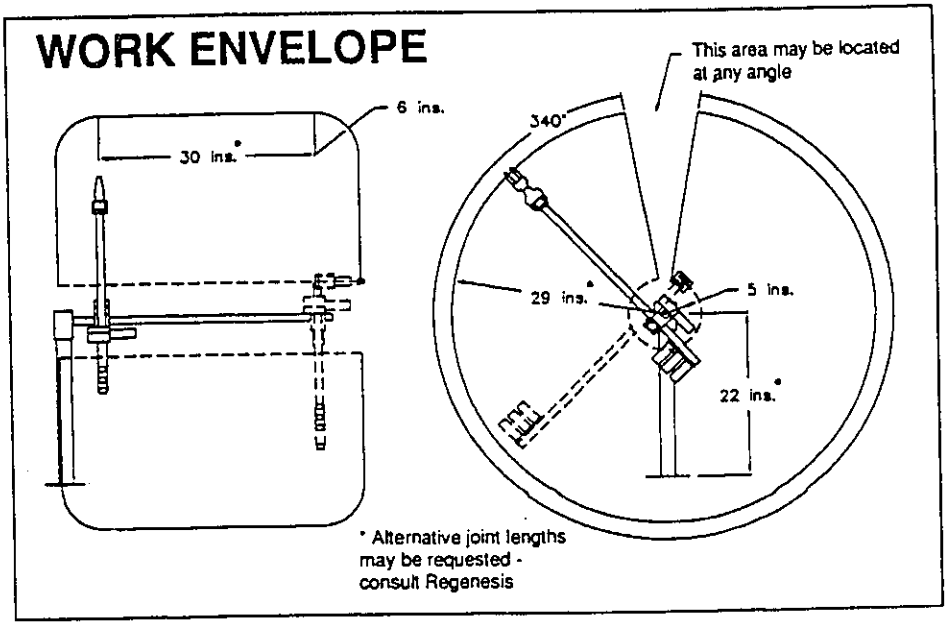

Figure 4.2: Work Envelope of Neil Squire Robot

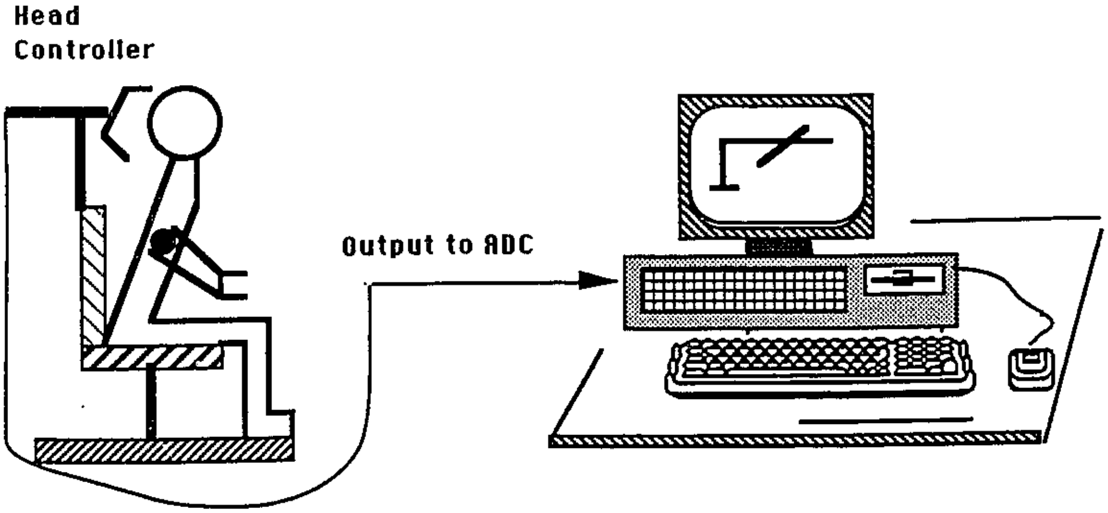

Figure 4.3: The Simulation System

4.3 The Simulation System

The hardware for our system includes a headset controller, an ADC card, and a 386/20 personal computer [Figure 4.3].

1. Headset controller.

The headset controller that we are using was designed by the Rehabilitation Institute, Montreal. It was originally mounted on wheelchair and used as a drive control by persons with quadriplegia. Its working principle is very simple. The power supply is added to the end points of a potentiometer. When the user moves his head, the output signal of this potentiometer changes. This signal is connected to the input of the ADC and is used to control the simulation.

2. ADC card

In order for our computer simulation to be controlled by the headset controller, the analog signal from the headset controller must be recognized by the computer. Therefore, an ADC card is needed to convert the analog signal to a digital signal. This digital signal can be used by the computer program. A PCL-812 Multi-Lab Card of Advantech Co. Ltd. was selected for our simulation [26].

The PCL-812 is a high speed, multi-functional data acquisition card for IBM and compatible personal computers. The function we are interested in is the analog input. An industrial standard 12-bit successive approximation converter (HADC574Z) is used to convert the analog inputs. The maximum A/D sampling rate is 30 KHz in DMA mode. There are three A/D trigger modes: Software trigger; Programmable pacer trigger; and External pulse trigger. It has the ability to transfer A/D converted data by program control, interrupt handler routine, or DMA transfer. We selected software trigger mode of program control. Based on the BASIC program that the producer provided, we rewrote the program in the C language.

3. Computer system

We have used an IBM compatible computer using an 80386 processor running at a speed of 20 MHz, with 1 MByte RAM and a Color monitor with VGA graphics card. All the simulation software was written using the Turbo C compiler.

4.4 The Software

The aim of our simulation is to make a computer image of the robot on the screen which the user can control by using the headset controller. The visual impression we want to give the user is that of controlling a real robot performing a specified task. For the simulation to be realistic, real-time motion of the picture has to be simulated and proper visual perspective has to be incorporated. These requirements were hard to meet using commercial computer graphics packages. Therefore, we developed all of the software ourselves. Figure 4.4 shows the image of the robot and the target on the screen together with a background which enhanced the impression of three dimensions.

The development of the software was based on the idea of modular design. Therefore, its debugging, testing, and maintenance are very easy. In C language, the modularity is realized through the use of functions. Therefore, in the following sections, we will discuss some of the more important functions in our simulation software.

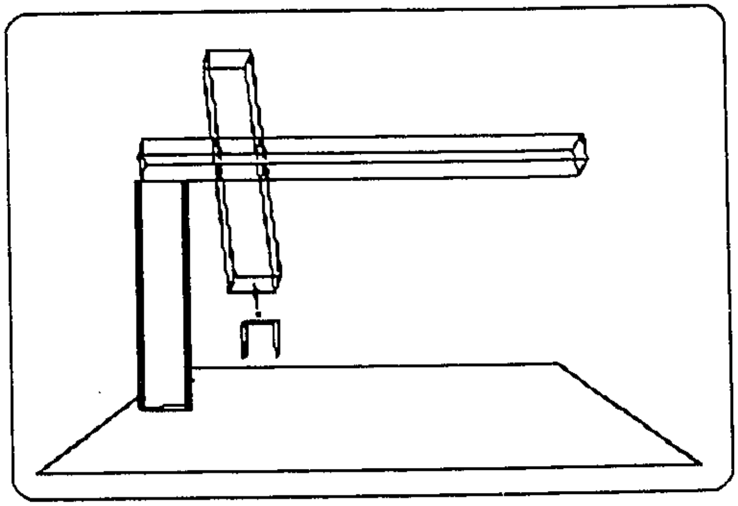

Figure 4.4: The Image of Simulation

The main function is used to control the flow of the whole software system. Figure 4.5 is a simplified flowchart of the main function. We will explain it step by step.

- The CRT is initialized to graphics mode.
- The ADC card is initialized.
- The name (input) of the user is read. This name is used to establish data files that contain all the results of this user.
- The selection of the linkage variable is read. This variable is used to set the linkage for a specified task.

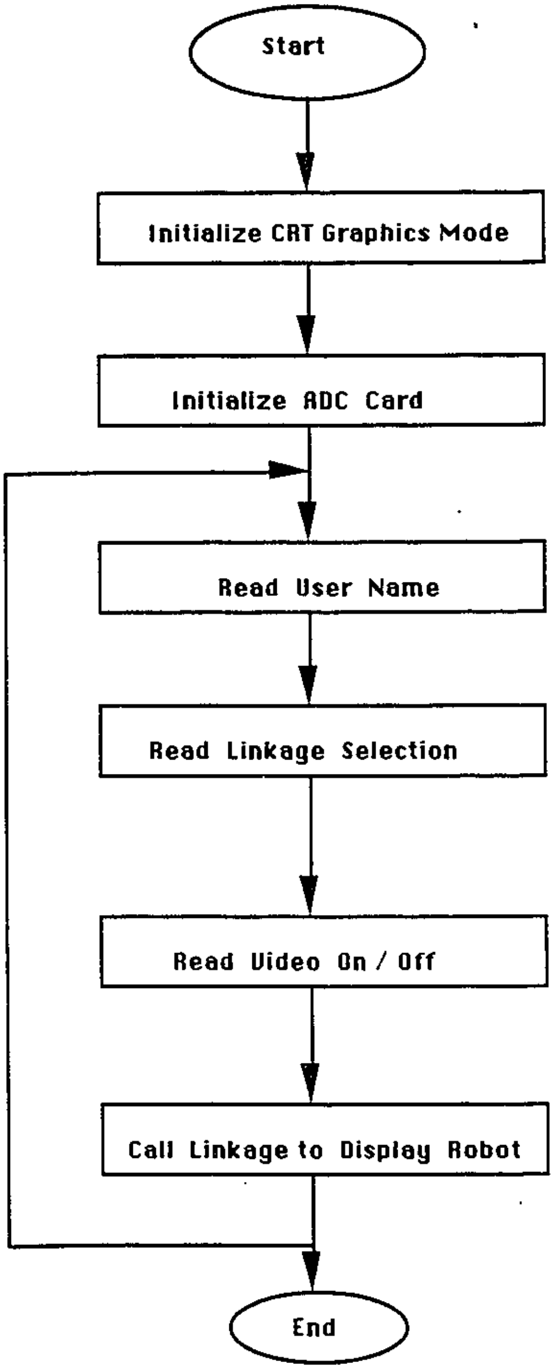

Figure 4.5: Flowchart of Main Function

- The selection of video on/off is read. This is used as part of the investigation of EPP. We will discuss it in detail in a later section.
- The linkage module, as determined by linkage selection, is called. This module is used to determine the motions of the robot.

Linkages are established to specify the different input-output relationships. Although linkage models (link1 and link2) are different from each other, their main flowcharts work the same. Figure 4.6 shows a simplified flowchart of the linkage function and we will explain it step by step.

- The position of the headset is read. This is the desired position to which the user wants the robot to reach.
- The dym function is called to determine the position that the robot can actually reach. This is based on the dynamic behavior of the actual robot and we will describe it in detail later.
- Several display functions are called to display different parts of the robot on the screen.
- A time delay function is called to make the sampling loop every 25 milliseconds.
- The program goes back to the first step. This function is in an infinite loop unless the user can quit from the program.

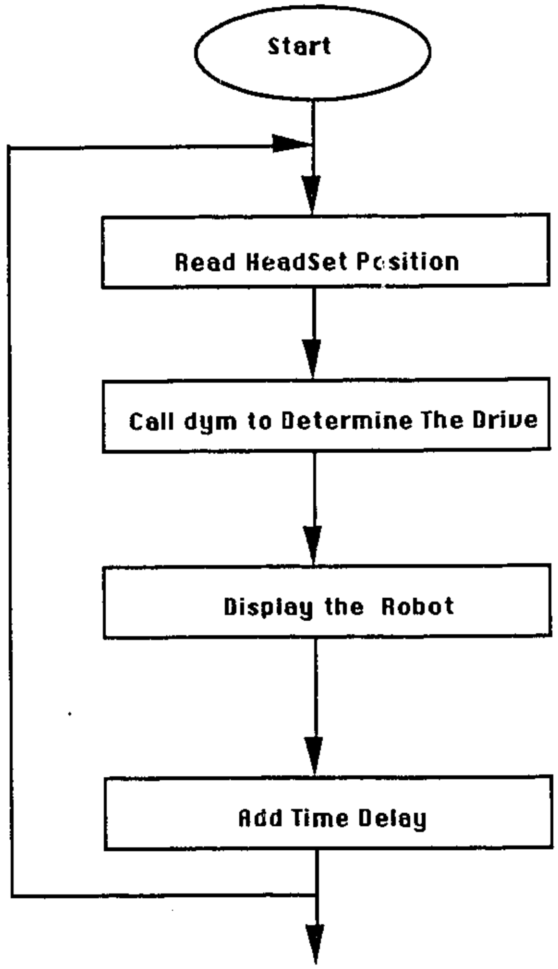

Figure 4.6: Flowchart of Linkage Function

One of the more important parts of the program is the three-dimensional display. In our program, the display function is divided into the column display, the track 1 display, the track 2 display, the gripper display, and the target display. Because all the displays are tied together, a calculation of a complex matrix transformation is needed. Figure 4.7 is the simplified flowchart of one of these display functions.

- The display points in local coordinates are defined.
- The transformation matrix is calculated using the Denevit-Harteburg technique.
- The positions of the points in eye coordinates are calculated.
- The points are projected onto the screen.
- The lines are drawn.

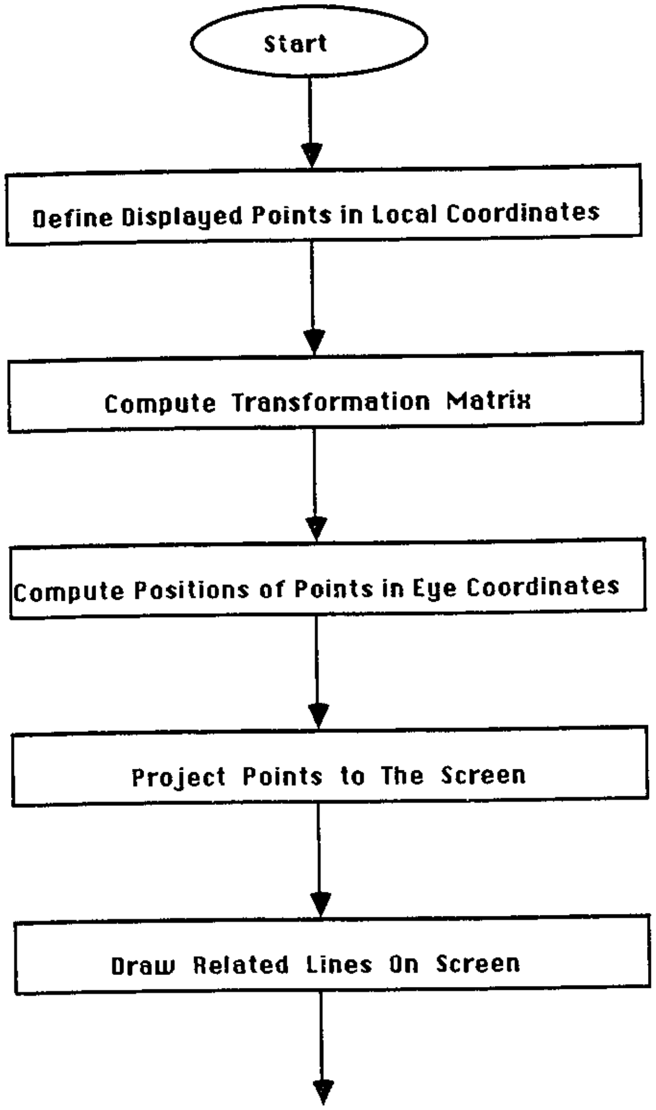

Figure 4.7: Flowchart of Display Function

4.5 The Linkage

One of the more important features of our simulation is the linked motion, which is called the linkage. A linkage is a predefined relationship between the input and output of all the related moving parts of the robot. A linkage is defined so that the robot gripper can follow the particular path in its work envelope when it performs a specified task. It also makes it possible for the one degree of freedom headset movement to control the multi degree of freedom robot. Furthermore, the linkage is selectable and this gives the user a wider range of tasks which can be performed.

In our simulation,the input is the headset position, and the output specified by the linkage is the position of the robot gripper. Regarding the head position and the gripper position, the relationship can be written as:

$$G = F(P_{head})$$

Where P_{head} is the position of the headset and G are variables related to gripper position. The function F is determined by different linkages.

There are two approaches to implementing a linkage. The first is to implement F analytically for each task. Then we can put the function F into the program and each time we have a P_{head} we always can get the position of the gripper by calculation. The advantage of this approach is that it is very accurate and straightforward to implement. The disadvantage is that the calculation may take time especially when the function is very complex. Also, it is usually very difficult to obtain an analytical expression for the function F if the coordinated motion is complex.

Another approach to implementing a linkage is to use look-up tables to determine the output. In this method, F is solved for every possible input position P_{head}, and the results are stored in a table. For each linkage, there is one such table. When the program is running, the table can be preloaded into memory, so the retrieval time is minimized. Also, this approach can be used whether or not an analytical expression is available for F. If the analytical function does not exist, a guiding (teaching) method can be used to find the input-output relationship. The disadvantage of this approach is that it requires large memory if the task is very complex.

In our simulation, the first approach is used to implement our two simple linkages. In the future, if a complex task is required, we can use the second method to establish the look-up table. For the present, we use linkage two as an example when we describe how to establish a linkage. Figure 4.8 shows linkage two. (Note that the selection of the coordinates is for the convenience of illustration).

In linkage two, the gripper can move along a predefined straight line which is connected by end points $(0,0,0)$ and $(300,150,100)$. Thus, we have:

$$\Delta_x = 300$$

$$\Delta_y = 150$$

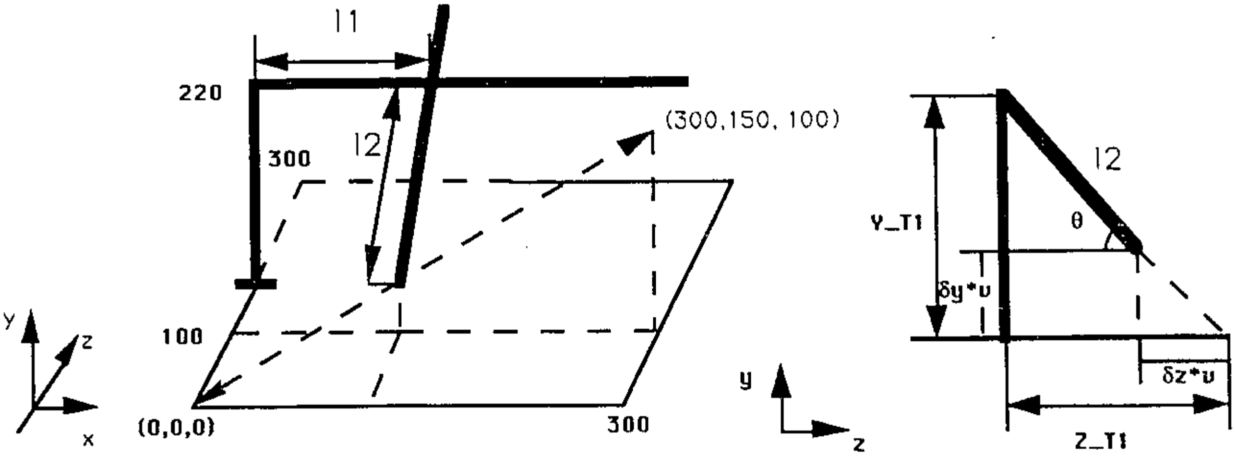

Figure 4.8: Linkage Two

$$\Delta_z = 100$$

If the headset moves through FSD volts, where $FSD = HEAD_{max} - HEAD_{min}$, we have for each volt:

$$\delta_x = \frac{\Delta_x}{FSD}$$
$$\delta_y = \frac{\Delta_y}{FSD}$$
$$\delta_y = \frac{\Delta_z}{FSD}$$

So after the voltage output (V) of the headset is read, we can obtain:

$$Output\ Point = (0,0,0) + (\delta_x, \delta_y, \delta_z)volts = \delta_x V, \delta_y V, \delta_z V$$

From Fig 4.8, we can derive the following variables:

$$l_1 = \delta_x V$$

$$l_2 = ((Y_{T1} - \delta_y V)^2 + (Z_{T1} - \delta_z V)^2)^{\frac{1}{2}}$$

$$tan\theta = \frac{Y_{T1} - \delta_y V}{Z_{T1} - \delta_z V}$$

$$\theta = arctan\frac{Y_{T1} - \delta_y V}{Z_{T1} - \delta_z V}$$

After the values of l_1, l_2, and θ are obtained, the position of the gripper is completely determined.

4.6 System Dynamics

4.6.1 Model

Given the force or torque of the actuators, the motion of the actual robot is determined by the dynamic behavior of the system. The dynamic equations relate forces and torques to positions, velocities, and accelerations of the robot. They are solved in order to obtain the equations of motion and thus to make the computer simulation as accurate as possible.

Our simulation system has six degrees of freedom. However the number of dynamic equations is not always six, as it depends on the linkage that is specified. In linkage one, track 2 moving along the track 1 is the only motion involved, so that only one dynamic equation is needed. Linkage two is more complicated. It

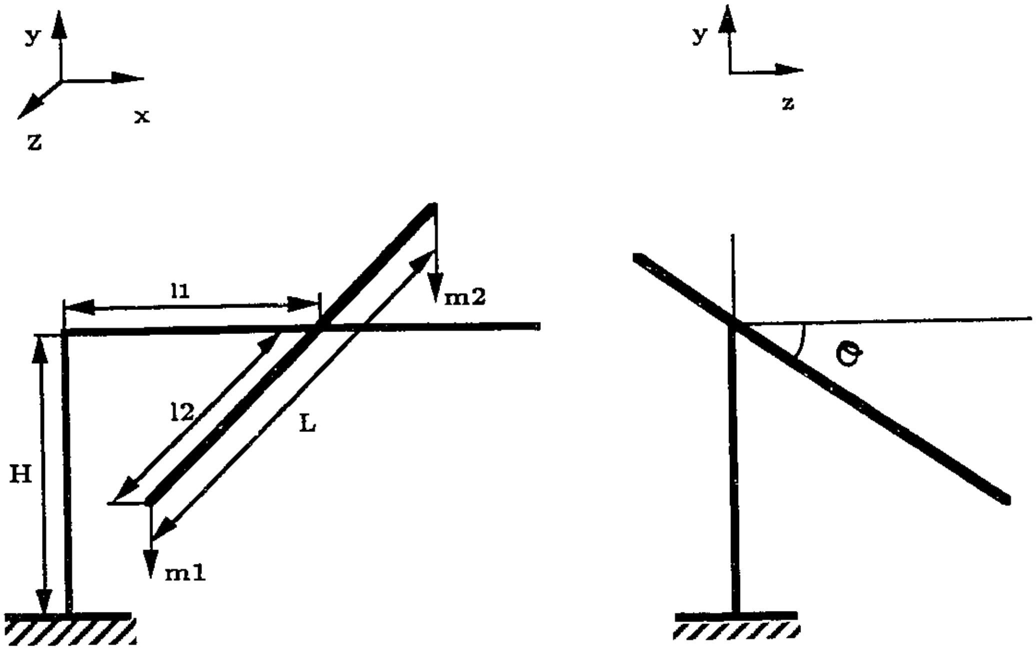

Figure 4.9: Dynamics of Linkage Two

has three degrees of freedom (the gripper does not yaw, pitch or roll), so that three dynamic equations are needed to control the movement. We use linkage two as our example when we discuss the dynamic equations [Figure 4.9]. l_1, l_2, and θ are the three variables which the actuators control.

The dynamic equations can be derived either from the Lagrangian method or from the Newton-Euler equations. The derivation resulting from the Newton-Euler approach is equivalent to the derivation using the Lagrangian method. However, the forms of the solution are different, and the form of the Newton-Euler solution requires less computation than does the equivalent Lagrangian solution [26]. Hollerbach [27] states that the recursive Newton-Euler formulation is more efficient than the recursive Lagrangian method. However the Lagrangian formulation is not so computationally intensive as to preclude real-time computation, as had been the assumption for the past 10 years. The Lagrangian formulation can, in fact, be made roughly as efficient as the Newton-Euler formulation. Hollerbach [27] also points out that for some applications involving the use of homogeneous coordinates, the recursive Lagrangian formulation may be the most convenient efficient dynamics formulation. In our simulation, the Lagrangian method will be used to derive the dynamic equations.

The Lagrangian of a mechanical system [26] is defined by:

$$L = K - P \tag{4.1}$$

where K is the total kinetic energy and P is the total potential energy of the system.

If an actuator is controlling a rotary variable, θ, then the torque seen by that actuator is

$$T = \frac{\partial}{\partial t}\frac{\partial L}{\partial \dot{\theta}} - \frac{\partial L}{\partial \theta} \tag{4.2}$$

Similarly, if the joint is prismatic, then the force applied in the direction of motion, x, is

$$F_x = \frac{\partial}{\partial t}\frac{\partial L}{\partial \dot{x}} - \frac{\partial L}{\partial x} \tag{4.3}$$

Now, considering our linkages, the following two assumptions will be made to simplify the problem.

1. Arms are much lighter than load m_1 or ballast m_2 and are therefore assumed to have no mass.
2. The masses of the load m_1 and ballast m_2 each act at a point.

We begin deriving the dynamic equation by finding the kinetic energy of the two masses. Considering load m_1 first, its Cartesian position is

$$x_1 = l_1$$

$$y_1 = -l_2 sin\theta$$

$$z_1 = l_2 cos\theta$$

We differentiate with respect to time to get the Cartesian velocity.

$$\dot{x}_1 = \dot{l}_1$$

$$\dot{y}_1 = -\dot{l}_2 sin\theta - l_2 cos\theta\dot{\theta}$$

$$\dot{z}_1 = \dot{l}_2 cos\theta - l_2 sin\theta\dot{\theta}$$

Then, the magnitude of the velocity vector is

$${V_1}^2 = (\dot{x}_1)^2 + (\dot{y}_1)^2 + (\dot{z}_1)^2$$

$${V_1}^2 = (\dot{l}_1)^2 + (\dot{l}_2)^2 + {l_2}^2(\dot{\theta})^2$$

The kinetic energy of a load m_1 moving at velocity V_1 is

$$K_1 = \frac{1}{2}m_1 V_1^2$$

So

$$K_1 = \frac{1}{2}m_1(\dot{l_1}^2 + \dot{l_2}^2 + {l_2}^2\dot{\theta}^2) \tag{4.4}$$

Similarly for ballast m_2, the kinetic energy is

$$K_2 = \frac{1}{2}m_2[\dot{l_1}^2 + \dot{l_2}^2 + (L - l_2)^2\dot{\theta}^2] \tag{4.5}$$

Now, we find the potential energy, using

$$P = mgh$$

where h is the height and g the acceleration of gravity

$$P_1 = m_1 g(H - l_2 sin\theta) \tag{4.6}$$

$$P_2 = m_2 g(H + (L - l_2)sin\theta) \tag{4.7}$$

The Lagrangian of the whole system is given by:

$$L = \sum K_i - \sum P_i \tag{4.8}$$

So

$$\begin{aligned} L \;\; = \;\; & \frac{1}{2}(m_1 + m_2)\dot{l}_1^2 + \frac{1}{2}(m_1 + m_2)\dot{l}_2^2 + \frac{1}{2}[m_1 {l_2}^2 + m_2(L - l_2)^2]\dot{\theta}^2 \\ & -(m_1 + m_2)gH + (m_1 + m_2)gl_2 sin\theta - m_2 gL sin\theta \end{aligned} \tag{4.9}$$

From equation (4.2), (4.3), and (4.9), the following three dynamic equations are derived, where F_{l_1}, F_{l_2}, and T_θ are the forces or torques to drive the motion of l_1, l_2, and θ respectively.

$$F_{l_1} = (m_1 + m_2)\ddot{l_1} \tag{4.10}$$

$$F_{l_2} = (m_1 + m_2)\ddot{l_2} - (m_1 + m_2)\dot{\theta}^2 l_2 - (m_1 + m_2)g sin\theta + m_2 L\dot{\theta}^2 \tag{4.11}$$

$$T_\theta = [m_1{l_2}^2 + m_2(L - l_2)^2]\ddot{\theta} - (m_1 + m_2)gl_2cos\theta + m_2gLcos\theta \tag{4.12}$$

Equation (4.10), (4.11), and (4.12) together provide a complete description of the dynamics of this linkage; that is, they provide a relationship between the torques or forces applied by the actuators and the resulting motion.

The dynamic equation for a D.C. motor [28] can be modeled as:

$$T_{motor} = J_m\ddot{\theta} + D\dot{\theta} + T_F + T_L \tag{4.13}$$

where:

T_{motor}: the torque that the motor provides.

J_m: the moment of inertia of the motor.

D: the friction torque of the motor.

T_F: the torque of the mechanical system related to friction.

T_L: the torque to drive the mechanical system; i.e. the torque or force that we get from Equation (4.10), (4.11) and (4.12).

We will ignore the velocity dependent torques for several reasons: they are very small compared to other torques, they are too complicated to solve for symbolically [29], and in our chosen example (the Neil Squire Robot), there are no specifications for the friction. Furthermore, friction is significant only when the robot is moving at high speed. Thus, the motor torque can be simplified to:

$$T_{motor} = J_m\ddot{\theta} + T_L \tag{4.14}$$

Now we have to decide on a strategy to control the ouput of the motor. Because when using equation (4.13), we assume that all the items related to velocity (e.g. friction) are zero, we will select a Propotional Derivative (PD) control in which the derivative item behaves exactly like the velocity item. The control equation is therefore:

$$Controller\ torque\ (or\ force) = K_e(q_d - q) - K_d\dot{q} \tag{4.15}$$

where:

K_e and K_d: the gain of the control equation.

q: the position or angular position respect to coordinate.

$\dot{q}$: the velocity or angular velocity.

q_d: the desired position or desired angular position.

If we use a D.C motor (4.14) to control the robot system and if we assume that the radius of the motor is r, the following three dynamic equations can be derived with respect to l_1, l_2, and θ

$$K_{e1}(l_{1d} - l_1) - K_{d1}\dot{l}_1 = (J_m/r^2 + m_1 + m_2)\ddot{l}_1 \tag{4.16}$$

$$K_{e2}(l_{2d}-l_2)-K_{d2}\dot{l}_2 = (J_m/r^2+m_1+m_2)\ddot{l}_2-(m_1+m_2)\dot{\theta}^2 l_2-(m_1+m_2)gsin\theta+m_2L\dot{\theta}^2 \tag{4.17}$$

$$K_{e3}(\theta_d - \theta) - K_{d3}\dot{\theta} = [J_m + m_1{l_2}^2 + m_2(L - l_2)^2]\ddot{\theta} - (m_1 + m_2)gl_2cos\theta + m_2gLcos\theta \tag{4.18}$$

We have to solve the above equations in order to get l_1, l_2, and θ with respect to time t. By analyzing the equations, we find that the equations (4.17) and (4.18) are nonlinear second order differential equations and also that the variables l_2 and θ are tied togather. Thus, it would be very difficult to solve them directly in real-time. Therefore in the next section, we will find a way to simplify the equations and solve them in real-time.

4.6.2 Real-time Approach

Although in linkage two the robot has three degrees of freedom, we can take into account that our sample time (0.025 second) is very small compared with operating time of robot and we can therefore assume that in this short interval each degree of freedom can be considered independently. Also, we have to take into account that the force or the torque which an actuator can supply is not unlimited. So we can, therefore, work out the following three independent dynamic equations.

1. Considering that only l_1 changes

The control equation in this case is exactly the same as (4.16), because it does not relate to the velocities of l_2, or of θ. We define $F_{req1} = K_{e1}(l_{1d} - l_1) - K_{d1}\dot{l}_1$ as the required force seen by the mechanical system and assume that it does not change during each sample time. Equation (4.16) therefore becomes:

$$(J_m/r^2 + m_1 + m_2)\ddot{l}_1 = F_{req1} \tag{4.19}$$

This is a second order homogeneous equation with double root $\lambda = 0$. So the general solution is:

$$l_1(t) = C_1 + C_2 t + \frac{F_{req1}}{2(J_m/r^2 + m_1 + m_2)} t^2 \tag{4.20}$$

Given initial position $l_1(t_0)$ and initial velocity $\dot{l}_1(t_0)$, we can obtain the values of C_1 and C_2,

$$C_1 = l_1(t_0) - \dot{l}_1(t_0) t_0 + \frac{F_{req1}}{2(J_m/r^2 + m_1 + m_2)} {t_0}^2$$

$$C_2 = \dot{l}_1(t_0) - \frac{F_{req1}}{J_m/r^2 + m_1 + m_2} t_0$$

2. Considering that only l_2 changes

If we assume that only l_2 changes, then the $\dot{\theta}$ is zero. Equation (4.17) therefore becomes:

$$(J_m/r^2 + m_1 + m_2)\ddot{l}_2 - (m_1 + m_2) g sin\theta = F_{req2} \tag{4.21}$$

where, $F_{req2} = K_{e2}(l_{2d} - l_2) - K_{d2}\dot{l}_2$ is the required force.

Since we assume that F_{req2} does not change during the sample interval, equation (4.21) can be rewritten as:

$$(J_m/r^2 + m_1 + m_2)\ddot{l}_2 = F_{req2} + (m_1 + m_2) g sin\theta \tag{4.22}$$

This is a second order homogeneous equation with double root $\lambda = 0$. The general solution is:

$$l_2(t) = C_1 + C_2 t + \frac{F_{req2} + (m_1 + m_2) g sin\theta}{2(J_m/r^2 + m_1 + m_2)} t^2 \tag{4.23}$$

Given initial position $l_2(t_0)$ and initial velocity $\dot{l}_2(t_0)$,

$$C_1 = l_2(t_0) - \dot{l}_2(t_0)t_0 + \frac{F_{req2} + (m_1 + m_2)gsin\theta}{2(J_m/r^2 + m_1 + m_2)}{t_0}^2$$

$$C_2 = \dot{l}_2(t_0) - \frac{F_{req2} + (m_1 + m_2)gsin\theta}{J_m/r^2 + m_1 + m_2}t_0$$

3. Considering that only θ changes.

The control eqution in this case is exactly the same as eqution (4.18), because the equation does not relate to the velocities of l_1, and l_2

Assuming T_{req} is the required torque seen by the mechanical system, the equation (4.18) becomes:

$$[J_m + m_1{l_2}^2 + m_2(L - l_2)^2]\ddot{\theta} - (m_1 + m_2)gl_2cos\theta + m_2gLcos\theta = T_{req} \qquad (4.24)$$

This is a second order nonlinear differential equation. By analyzing the linkage, we find that the change of θ is very small. So during our small sample interval, $cos\theta$ can be considered to be constant. We rewrite the equation (4.24) as:

$$(J_m + m_1{l_2}^2 + m_2(L - l_2)^2)\ddot{\theta} = T_{req} + (m_1 + m_2)gl_2cos\theta - m_2gLcos\theta \qquad (4.25)$$

The right side of the equation is, therefore, a constant and the general solution is:

$$\theta(t) = C_1 + C_2t + \frac{T_{req} + (m_1 + m_2)gl_2cos\theta - m_2gLcos\theta}{2[J_m + m_1{l_2}^2 + m_2(L - l_2)^2]}t^2 \qquad (4.26)$$

Given initial position $\theta(t_0)$ and initial velocity $\dot{\theta}(t_0)$ of each sample interval, we can obtain the values of C_1 and C_2,

$$C_1 = \theta(t_0) - \dot{\theta}(t_0)t_0 + \frac{T_{req} + (m_1 + m_2)gl_2cos\theta - m_2gLcos\theta}{2[J_m + m_1{l_2}^2 + m_2(L - l_2)^2]}{t_0}^2$$

$$C_2 = \dot{\theta}(t_0) - \frac{T_{req} + (m_1 + m_2)gl_2cos\theta - m_2gLcos\theta}{J_m + m_1{l_2}^2 + m_2(L - l_2)^2}t_0$$

Equations (4.20), (4.23) and (4.26) are the dynamic equations that will be put into the simulation program. In linkage two, we use one input to control the three degrees of freedom coordinated motion, so the three variables must be tied together. In each sample time, we first solve three dynamic equations in parallel, and then follow the one which has the slowest movement and let the other two motions be tied to that motion according to the linkage. Using this method, the complexity of the equation is significantly simplified, so that the real-time calculation becomes possible.

4.6.3 Performance of the Dynamic System

As we metioned above, by putting the dynamic equations into the computer program and solving them, we can obtain the motion of a robot as a function of time. The performance of the motion depends on the parameters of the dynamic equations, i.e. the gain, the load and the inertia of the motor. By choosing these parameters, the motion can be critically damped, underdamped, or overdamped [28].

In our simulation, we assume that the inertia of the motor is 2 x 10^{-4} $kg-m^2$, the radius of the motor is 1 x 10^{-2} m, the ballast is 1 kg, and the load is 2 kg.

Now, by selecting the gain K_e and K_d, we can make the motion critically damped. We can rewrite the Equation (4.16) as follows:

$$(J_m/r^2 + m_1 + m_2)\ddot{l_1} + K_d\dot{l_1} + K_e l_1 = K_e l_{1d} \tag{4.27}$$

The corresponding characteristic equation is

$$(J_m/r^2 + m_1 + m_2)\lambda^2 + K_d\lambda + K_e = 0 \tag{4.28}$$

The roots are given by

$$\lambda = \frac{-K_d \pm \sqrt{{K_d}^2 - 4K_e(J_m/r^2 + m_1 + m_2)}}{2(J_m/r^2 + m_1 + m_2)} \tag{4.29}$$

Thus the motion depends on the term ${K_d}^2 - 4K_e(J_m/r^2 + m_1 + m_2)$. We denote this value by T. If $T = 0$, the motion is critically damped, i.e. a robot gripper can get to the desired position without overshoot and without oscillation. If $T > 0$, the motion is overdamped, i.e. a robot gripper can get to the desired position without oscillation after a sufficiently long time. If $T < 0$ the motion is underdamped, i.e. a robot gripper can be at rest in the desired position after damped oscillation.

In our simulation, the selection of the gain is made to achieve the critical damping. Therefore, if we let $K_e = 7500$, we can get $K_d = 387$.

Based on the above K_e and K_d, we can see how the load and the motor inertia affect the performance of the control. First, we change the value of load m_1. If we let $m_1 = 3\ kg$, then $T < 0$, and the system becomes underdamped. If we let $m_1 = 1\ kg$, then $T > 0$, so the system becomes overdamped. Given a step input, we can see the results in figure 4.10. We now change the the value of motor inertia

J_m. If we let $J_m = 3 \text{ x } 10^{-4}\ kg - m^2$, then $T < 0$, and the system becomes underdamped. If we let $J_m = 1 \text{ x } 10^{-4}\ kg - m^2$, then $T > 0$, so the system becomes overdamped. Given à step input, we can see the results in figure 4.11.

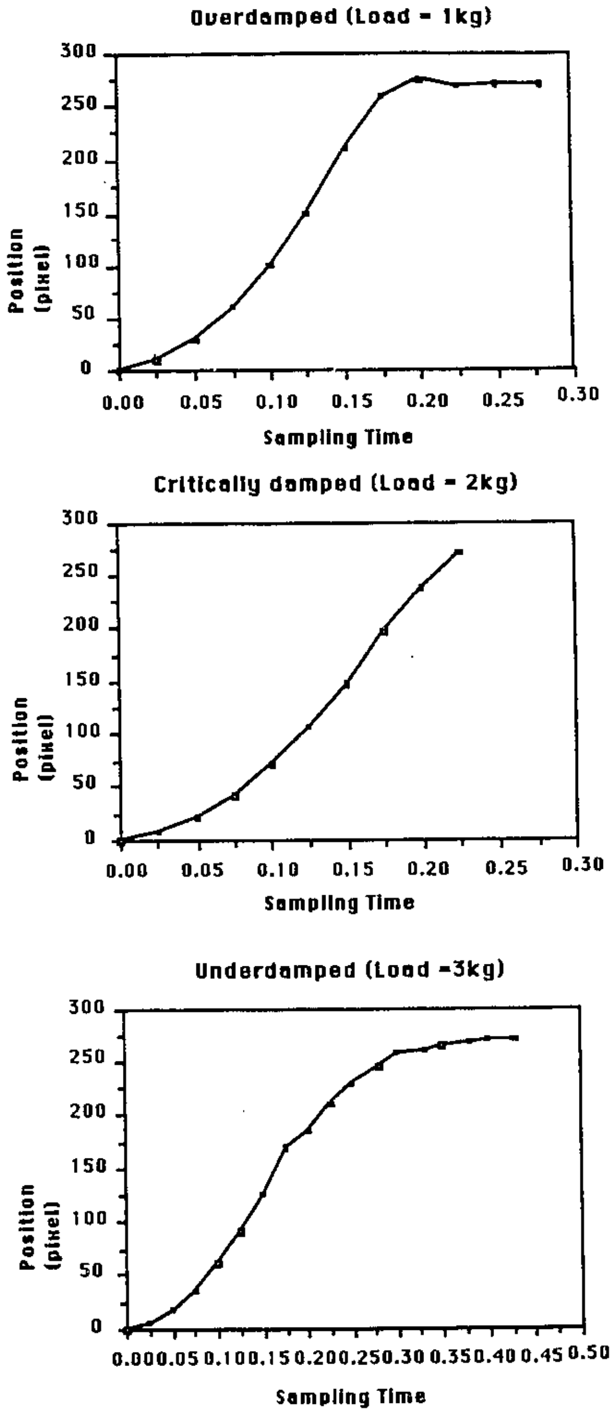

Figure 4.10: The Effect of Load on Motion

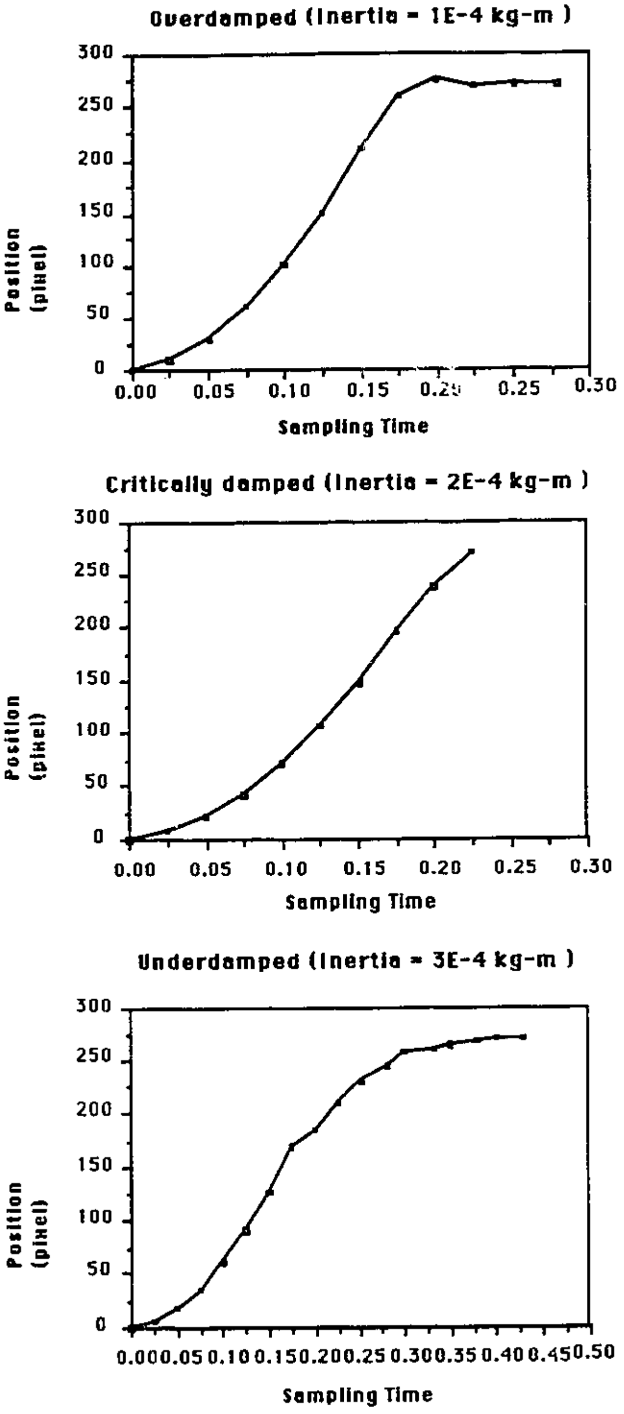

Figure 4.11: The Effect of Inertia on Motion

4.7 Learning Protocol

One of the objectives of our computer simulation of robots for disabled persons is to investigate different control strategies. At present, we are interested in the control strategy called Extended Physiological Proprioception. Thus, in our computer simulation, we designed a learning protocol to teach users how to use EPP. In future work, the efficiency of EPP can therefore be precisely analyzed.

Learning to use EPP makes use of video on and video off. The video on means that both robot and target are shown on the screen and reaching the target is relatively easy. The video off means that only the target and the background are shown on the screen, but not the actual robot. The operation of EPP here is described in the following sentences. By using video on, the user can learn the position of the gripper corresponding to the position of the headset. When using the video off, he can use the learned association of the position of gripper and the position of the headset to get to the target even without being able to see the actual position of the gripper. This is exactly like the training of a tennis player. After he has trained for some time, he will not need to look at the racquet to know where it is.

The procedure of learning works as follows (see also Figure 4.12, 4.13):

- At the begining of the training, the user enters his own name so that all the data related to his training can be recorded under his name.

- The selection of video on/off is read by the computer.

- The selection of the linkage is read by the computer. The user can select the linkage for a specified task.

- The user starts the task by moving his head to the far left (the robot gripper therefore moves to the far left) until he hears a beep. At this time, the target is displayed on the screen and the clock starts counting.

- The user moves the robot gripper to the target and presses the key 'g' to finish grasping. For disabled subjects, they can use an EMG or other switch. The computer counts the time which the user takes to finish the grasping and also records the accuracy of the positioning.

- The user can release the target at any position by pressing the key 'r'.

- The program is in an infinite loop. Therefore, the user can move his head to the far left to start another test. Note that the position of target of each test can be determined either by the researchers or randomly by the computer.

There are two types of data files to be estabilished: one single file to record the time and accuracy for all the tests; the other group of files to record the complete time-position data for each test.

Having obtained the above data, it is possible to analyze the results of a particular EPP strategy and it is possible to compare this result with other control strategies.

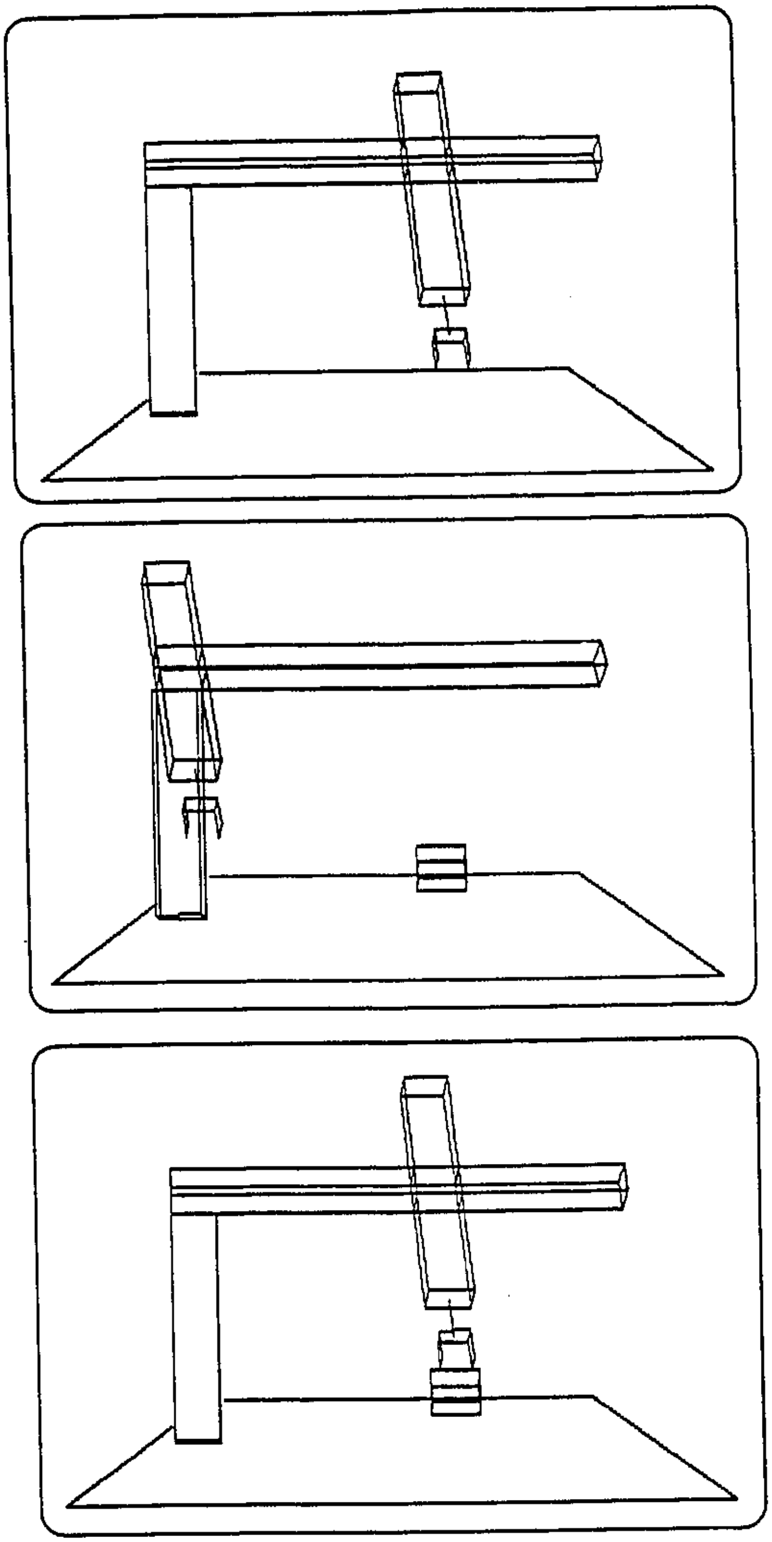

Figure 4.12: The Learning of EPP with Visual On

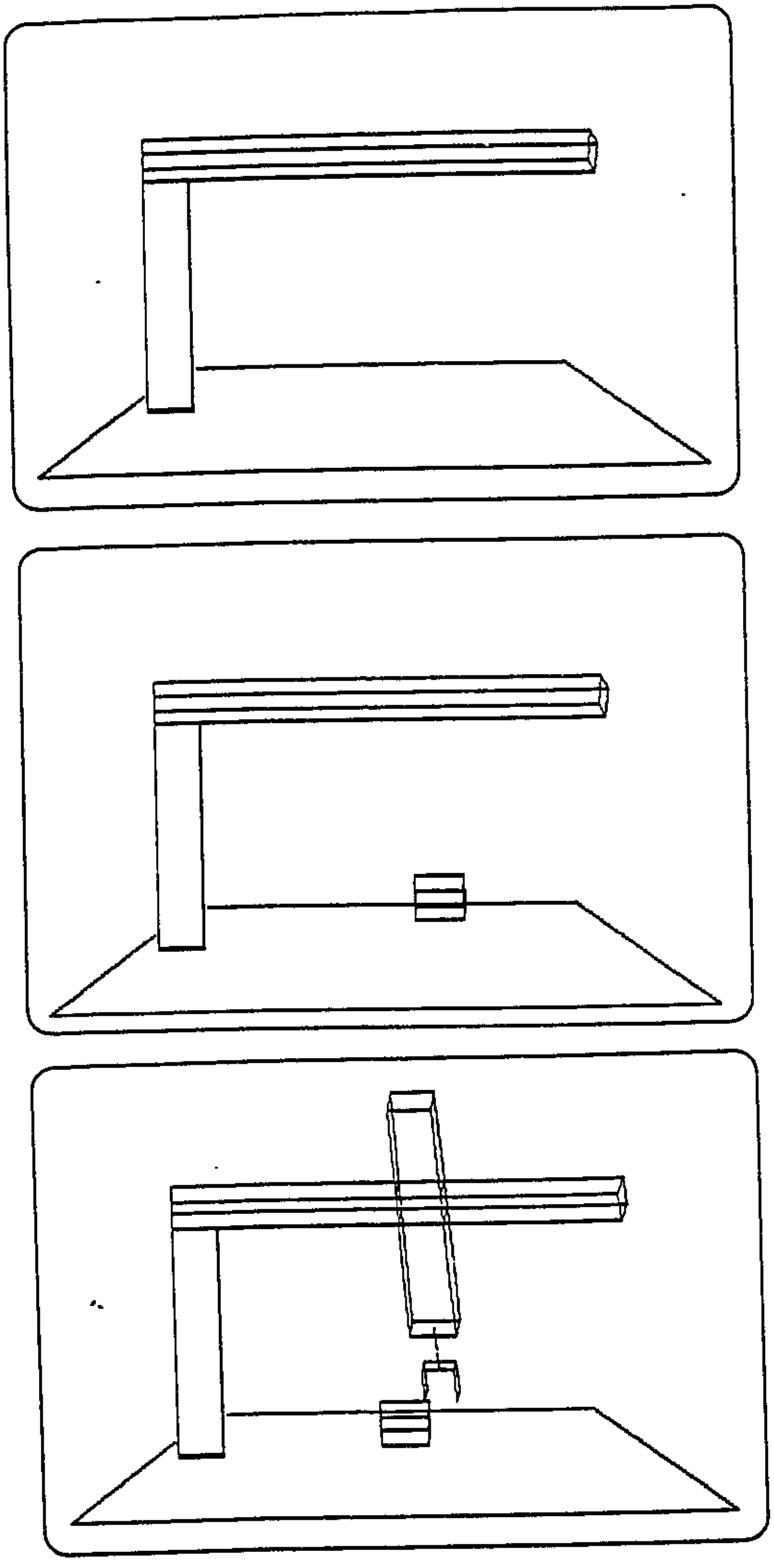

Figure 4.13: The Learning of EPP with Visual Off

Chapter 5

Conclusion

A computer simulation of robots for disabled persons has been described. This system can be used by researchers to investigate control algorithms for a personal robot. It can also be used by disabled persons so that they can get familiar with the robot as well as the control strategy before they use or purchase the actual model. Our six degrees of freedom simulated robot is controlled, in a coordinated manner, using a modified form of EPP (extended physiological proprioception). The movement of the head has been selected as the controlling input. The relationship between input and output is determined by a set of selectable predefined linkages.

The wide variety of personal robot systems, the different possible realizations of our modified EPP control, the ever-present risk of injury from preliminary prototypes, and the need for accurate measurements, made us decide to use three-dimensional computer simulations rather than actual robots. The computer simulations were programmed in C.

Our control strategy is based on a modification of the control modality introduced by D.C. Simpson. In the original EPP, as designed for multi-functional upper-extremity prostheses, a 1:1 relationship was established between the positions of intact joints and the position in space of the terminal device. With such a control strategy, the operator can have excellent proprioception of the position of the terminal device. However, the range of potential tasks is constrained by the single input-output relationship. The advances in microcomputer technology have made it possible to move away from the mechanically-induced constraints of the original EPP system and to supply the user with a range of several input-output relationships from which to choose. While this change will certainly increase the number of tasks which can be performed, we can expect a loss of position proprioception and also a reduction in speed. In the future, a full investigation of our control strategy is needed to quantify both the functional gains and the losses in position accuracy and speed as compared with conventional EPP systems. In our simulation, we have implemented two linkages as a preliminary phase of the overall research in this area. In the future work, more linkages can be implemented for a series of special tasks. If a linkage is too complex to implement as an equation, the look-up table method can be used.

Our system produces a realistic three-dimensional display of the robot under study, along with its inputs and the system dynamics. We have investigated the influence of the motor inertia and the load on the performance of the system. In the future, by putting different parameters of motors into the program, we can simulate many kinds of personal robots. The computer simulation program also controls the experiments and compiles the results.

The preliminary tests we have performed have established that users of personal robots can learn more than one input-output relationship, thereby increasing the range of functions for such devices without compromising safety. In addition, the three-dimensional simulation has been shown to be a useful, appropriate, easily adaptable, and a completely safe method for prototype development.

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