Development of the Web-Based Control Laboratory and Long Distance Education

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Content

Abstract

Internet has been widely used in education as an effective medium of communication since 1990s. Traditionally, the Internet has mainly been used for teaching materials dissemination through the world-wide-web. In recent years, Internet has played more important role in long distance education. An exemplifying application of the Internet in long distance education is the development of the Internet based laboratory that allows the engineering and science experiments to be conducted anywhere at any time through the access of a web browser. At the Chinese University of Hong Kong, we have been developing an Internet based control laboratory since 1999. The development has undergone two phases. In phase 1, we focused on the prototyping design which mainly involves the integration of different computer languages, different operating systems, and different hardware suites. The core of the development is to provide a server system that can communicate with the instruments so that certain control experiments can be interactively carried out from the client side. Two prototype designs, namely, the DC motor experiment and the coupled tank experiment were set up for validating the design. This phase was successfully completed in the summer of 2001. The development entered its second phase in the late 2001. The second phase has been focusing on four parts. In the first part, we consolidate the phase 1 research. The second part is to further expand the scope of the development of the laboratory by setting up two more experiments: the mass-spring-damper system and the ball and beam system. In the third part, we design various control experiments using several systems as platforms. These experiments encompass both classical control and modern control ranging from system modeling, frequency response, bode plots to various frequency design methods such

as PID control and lead-lag control and state space design methods such as pole placement, feed-forward control and internal model control. All experiments are menu-driven with the open architecture feature. Students can not only test the built-in controllers, but also test the controller designed by themselves through changing the parameters of the controller online. Thus, this Internet based control laboratory not only offers students more opportunities for hands-on experiments, but also allows the students to explore and create their own designs. The fourth part of the phase 2 is to evaluate the validity of this laboratory through user testing. So far, the DC Motor control experiment has been tested in the spring semesters of year 2001-02 and year 2002-03 by third year undergraduate students. The experiments are incorporated into the teaching of the course ACE3010 Modern Control Analysis and Design. Our experience shows that the development of Internet based laboratory has enabled the control experiments to be conducted in a routine homework assignment, and been an effective educational tool for learning and teaching.

So far, the objectives of phase 2 have been achieved. This thesis is a documentation of my efforts in carrying out the development of Phase 2. The web-based laboratory realizes the integration of theoretical and practical study in science and engineering. And it enhances the learning and teaching quality. I believe that this Internet based control laboratory has brought the application of the Internet to a new horizon, and at the same time, given a new technique to long distance education.

摘　要

自上個世紀九十年代以來，互聯網作為一種高效的通訊媒體已廣泛地應用於教育領域。傳統上，互聯網主要用於教學材料的發佈。但是，近年來互聯網在遠程教育中扮演著越來越重要的角色。一個典型的例子就是基於互聯網的實驗室的發展。這種實驗室允許人們在任何時候任何地方通過一台電腦終端去執行工程或科學實驗。自 2000 年以來，香港中文大學自動化與計電腦輔助工程學系一直致力於發展一個基於互聯網的控制實驗室。該課題經歷兩個階段。在第一階段，我們主要致力於實驗原型設計。它涉及各類不同電腦語言、不同運行系統和不同的硬件設備的整合。該階段研究的核心在於提供一套服務系統，它既能與實驗室的儀器溝通，又能向實驗者提供互動介面。在此階段，我們設計了兩套實驗，即直流馬達系統和藕合水箱系統，用以驗證設計的可行性。該階段已于 2001 年夏順利完成。

第二階段主要包括四部分。一是鞏固第一階段的設計。二是通過建立另外兩套實驗來進一步拓展網上實驗室，即振子彈簧阻尼系統和棒球系統。三是以這些系統為平臺設計各類控制實驗，包括經典控制和現代控制，從頻率回應特性研究，波特圖繪製，系統建模，各種頻域設計方法比如 PID 控制和超前滯後控制，到狀態空間設計方法比如極點配置，前饋控制和內模控制等等。所有的實驗都具備開放結構特徵，學生不僅可以測試系統內置的控制器，而且可以通過改變控制器的參數來測試自己所設計的控制器。因此，基於互聯網的控制實驗室不僅提供學生更多的機會執行手動實驗，而且允許學生探究創建自己的控制器。第四部分是通過用戶測試來評估實驗室的可行性。其中直流馬達控制實驗已經應用於本科課程“現代控制分析與設計”。經過 2001-2002，2002-2003 兩學年的測試，已證明基於互聯網的控制實驗室完全可以作為本科教學的一個輔助工具。

到目前為止，作者已經順利地完成了第二研究階段。該論文是對該階段作者所做的研究的總結報告。作者相信基於互聯網的控制實驗室的發展已使互聯網的應用達到一個新的水平，並為遠程教育提供了一項新的技術。

Chapter 1

Introduction

Nowadays, Internet has entered our daily life as a medium of communication with an ever expanding scope. At the same time, the rapid development of the world calls for more convenient and effective study environment. Thus, the Internet-based long distance education, a sign of entrance of education into the information technology era, has become a hot developing point of education reform. This thesis summarizes the research outcomes of the candidate on the topic of developing the web-based control education and its application to long distance education. This chapter will give an overview on the current research, especially, on the web-based laboratory, summarize our project of the development of the web-based control laboratory, and outline the thesis.

1.1 Long Distance Laboratory

Long distance education can be classified into two categories, i.e., *theory education* and *laboratory education* [2, 3, 5, 15, 21]. Most of the programs of theory education are implemented by the medium such as course e-mail, course home page, discussion group, etc. And these applications are based on the full-grown technologies, such as e-mail, World Wide Web. But, the essence of laboratory education is based on practicing, operating and observing in person. Therefore, compared with the theory education, the long distant laboratory education is much more complicated. Currently, on one hand, laboratory education is the weakness of the long distance education. On the other hand, it is the important mode in education, especially, for the students majoring in engineering and science.

To solve the problem of inconsistence between the development and requirement of long distance laboratory education, more and more institutions around the world have been doing the research on this field. Two of the important outcomes are the Demonstration Laboratory (DL) and Virtual Laboratory (VL), developed over the past years [7, 8, 16].

DL utilizes the memory and propagation ability of the computer network to reproduce the experiment scene. It usually has the following functions: acquiring and analyzing the experimental data using computer, showing the fictitious experiment with the computer, delivering the relevant guidance experiment materials through Internet, including the various multimedia materials, e.g., picture, electronic slide, teaching material, etc. Therefore, DL allows students to observe the experiment indirectly, but doesn't offer students the chance to operate the experiment.

VL allows students to continuously access their hypothetical experimental setups. The major advantage of VL paradigm is the minimal cost needed to set up a laboratory, as it only requires a robust communication network. As we know, the resource of hardware is always expensive and hardly built. In the point view of resource configuration, it makes share of software, i.e., the software package of the hypothetical setups. However, VL concept only provides the users with theoretical and simulation materials. It is still far from real engineering experiment where it is important to explore the real experimental phenomenon and feedbacks.

More recently, there is a trend at many institutions around the world [1, 10, 13, 14, 17, 22, 23, 30] to develop a long distance experiment teaching mode which has traditional real feeling and can run in the objective environment. Internet-based laboratory (or web-based laboratory) is just a new mode of "Virtual" (virtual instrument panel) + "Entity" (equipment entity of the hardware) + "Real" (real experiment scene). It possesses all advantages of the DL and VL. It is the advanced concept of distance education that enables students to perform experiments in real time through Internet. As a result, the users can share the resources of hardware while sharing the recourses of software. This can be meaningful particularly in engineering education.

From above, the development of long distance laboratory can be summarized as follows.

- Demonstration Laboratory only exhibits the demonstration of experiments.
- Virtual Laboratory utilizes multimedia animation or simulation technologies to establish virtual experiment environments.
- Web-based laboratory enables users to perform experiments in real time through Internet.

1.2 Overview of Web-Based Laboratory

Since 1990, many institutions have been developing the web-based laboratory. In 1998, the Oregon State University developed a real-time remote-access control engineering teaching laboratory [1] where the system "Second Best to Being There (SBBT)" provided a Java interface on the client's browser to conduct the robot experiment. In the next year, Control Engineering Laboratory of Polytechnic University of New York designed a generic virtual instrument for real-time experiments [17]. The philosophy behind the Internet-accessed remote laboratory is based on a client/server computer configuration. However, it requires users to download a LabVIEW based package and run the platform to carry out the remote experiment.

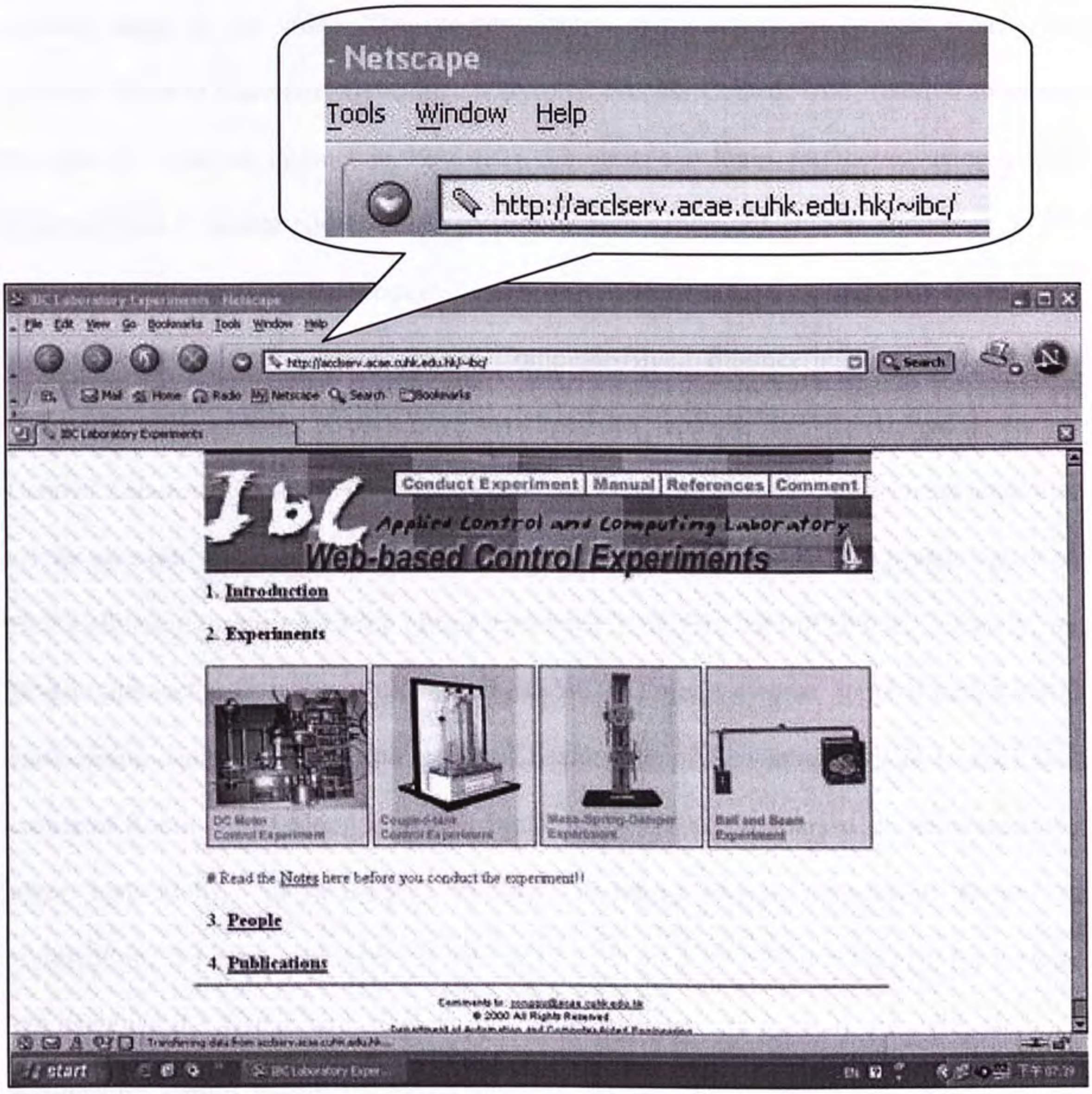

Figure 1.1 Homepage of the Web-Based Laboratory

A remote laboratory called VLAB on an oscilloscope experiment was set up at The National University of Singapore in 1999 [14]. Later, other three experiments were developed. They are coupled tank experiment, helicopter experiment and frequency modulation experiment. Among them, the setup of coupled tank experiment used video conferencing to provide the point-to-point visual feedback and allow control of zoom and viewing angle of the video. The Process Control and Automation Laboratory at Case Western Reserve University developed a Byronic Process Control Unit, referred to as the process rig, over the Internet in 1998 [22]. The user can login parameters using a web browser from a remote client to a LabVIEW G web server, which was connected to the process rig via a PLC control module.

At the Department of Automation and Computer-Aided Engineering (ACAE), Chinese University of Hong Kong (CUHK), we have been developing a *Web-Based Remote-Access Control Laboratory* since 1999 [25, 26]. Our purpose is to create an experiment setup that can be accessed anywhere at anytime by specified users. In particular, the system has been practically used for the education of undergraduate in modern control course. Currently, we have implemented four sets of systems, those are, DC motor system, coupled tank system, mass-spring-damper system, and ball and beam system. The laboratory is located at a corner of Room 305 of Mong Man Wai Building at CUHK. Compare with the work of the other institutions, our web-based control laboratory has a remarkable feature in architecture. We have used layers as entities that can work on different tasks in the system. We designed the system with modularity. All experiments are menu-driven with the open architecture feature. Figure 1.1 shows the main page of the lab which can be accessed via *http://acclserv.acae.cuhk.edu.hk/*.

1.3 Project of Development of Web-Based Laboratory

The project of development of web-based control laboratory has undergone two phases.

In phase 1, we focused on the prototyping design, which mainly involves the integration of different computer languages, different operating systems, and different hardware suites. The core of the development is to provide a server system that can communicate with the instruments so that certain control experiments can be interactively carried out from the client side. Two prototype designs, namely, the DC motor experiment and the coupled tank experiment were set up for validating the design. This phase was successfully completed in the summer of 2001.

In the second phase, we attempt to make the system more flexible, more interactive and have more designing efficient, thus, with more application value.

To achieve this objective, we develop the research on four tasks, which are not only research objectives but also research results.

- The first one is to consolidate the phase 1 research.
- The second one is that we further expand the scope of the development of the laboratory: the mass-spring-damper system and the ball and beam system.
- In the third task, we design various control experiments using several systems as platforms. To help students to know the control technologies widely, applying the appropriate control concepts on the respective control experiment is more important. These experiments encompass both classical control and modern control ranging from system modeling, frequency response, Bode plots to various frequency design methods such as PID control and lead-lag control and state space design methods such as pole placement, feedforward control and internal model control. All experiments are menu-driven with the open architecture feature. Students can not only test the built-in controllers, but also test the controller designed by themselves through changing the parameters of the controller online. We aim to make our laboratory not only offer students more opportunities for hands-on experiments, but also allow the students to explore and create their own designs anywhere at anytime.

- The last one is to evaluate the validity of this laboratory through user testing, which is important to guarantee the success of the laboratory. So far, the DC Motor control experiment has been tested in the spring semesters of year 2001-02 and year 2002-03 by third year undergraduate students. The experiments are incorporated into the teaching of the course "ACE3010 Modern Control systems Analysis and Design". Our experience shows that the development of web-based laboratory has enabled the control experiments to be conducted in a routine homework assignment.

1.4 Thesis Outline

The remaining chapters of this thesis are organized as follows.

In Chapter 2, an overall picture of the laboratory will be given, including four sets of systems, i.e., DC motor system, coupled tank system, mass-spring-damper system and ball and beam system.

Chapter 3 will describe the essential hardware and software architectures of the each set of system.

Chapter 4 will give a brief introduction on control methodology including basic control concepts, system modeling, and various controller design methods.

In Chapter 5 and Chapter 6, the mass-spring-damper system and the ball and beam system will be analyzed in details. Also, the corresponding various experiments design will be discussed.

Chapter 7 will turn to the education practice.

Finally, Chapter 8 will conclude this thesis and envision the future work.

Chapter 2

Laboratory Layout

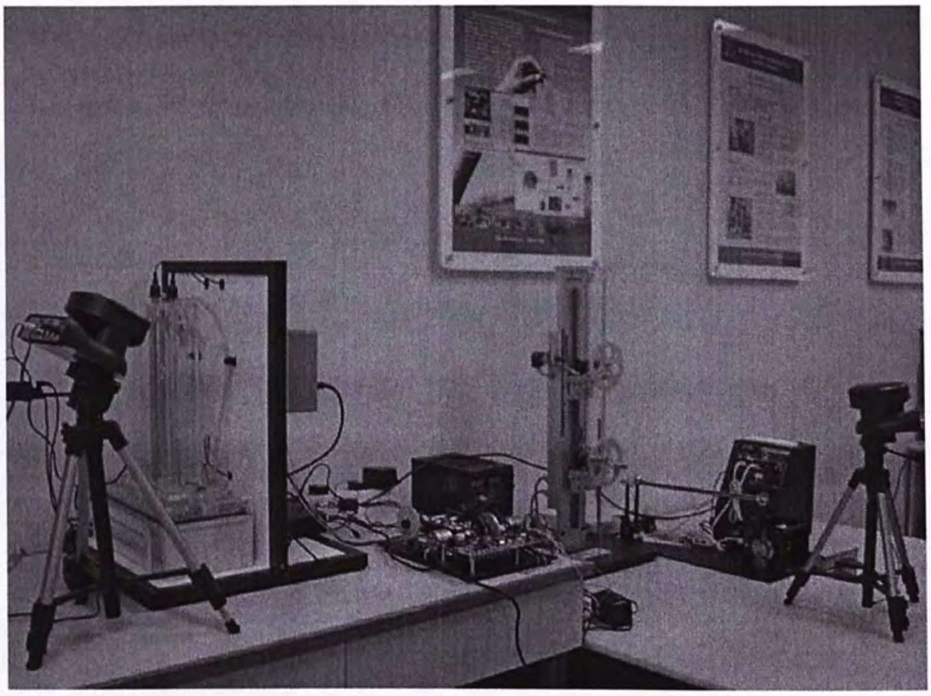

Figure 2.1 Laboratory Layout

The web-based laboratory is located at a corner of Room 305 of Mong Man Wai Building at CUHK. Figure 2.1 shows the layout of the laboratory. Right now, the laboratory hosts four sets of experiment instruments including a DC motor system, a coupled tank system, a mass-spring-damper system, and a ball and beam system. Each of them is independent in hardware and software. Therefore, the experiments can be conducted simultaneously by different users. Among the four systems, the DC motor system features the position and speed control, and the coupled tank system offers the water level control. The mass-spring-damper system is mainly used for studying the frequency response of a linear system. The ball and beam system is mainly used for the study of the set-point control of an unstable nonlinear system. This chapter will give the brief introductions of these four sets of systems. More detailed descriptions on the mass-spring-damper system and ball and beam system will be given in chapters 5 and 6, respectively.

2.1 DC Motor System

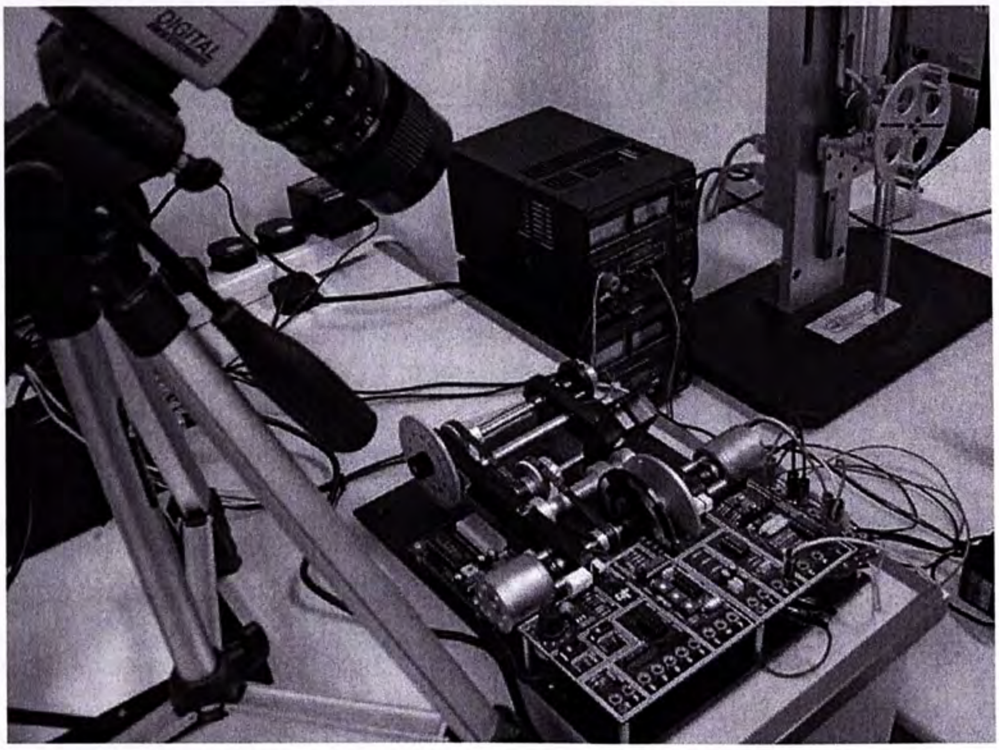

Figure 2.2 DC Motor Module

The MS15 DC Motor control Module shown in Figure 2.2 enables the user to perform position control by general state space controller or speed control by PID controller. The speed and direction of rotation of the motor can be controlled by either an analogue signal or a pulse width modulated (p.w.m.) digital signal.

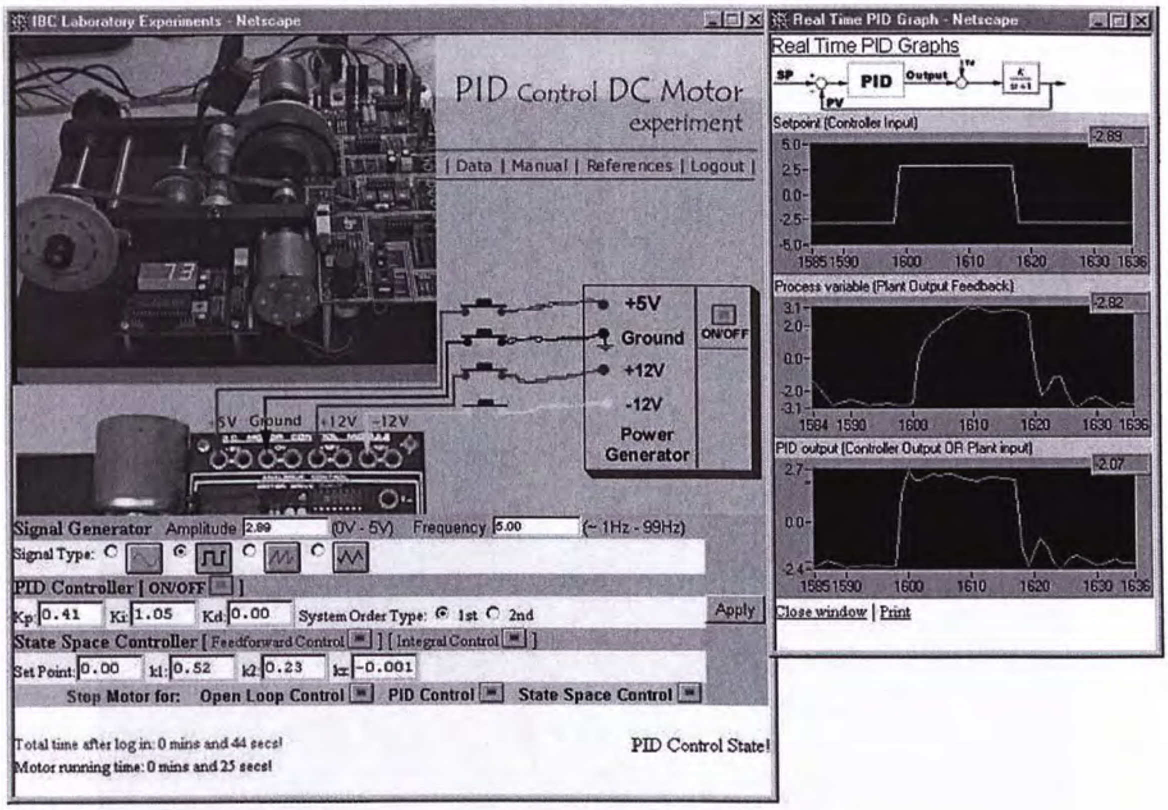

Figure 2.3 DC Motor Experiment Interface

Based on this set of system, four experiments are designed to investigate the open loop properties of the DC motor and the behaviors of different controllers applied, as listed below. And the experiment interface is demonstrated in Figure 2.3.

- Open loop speed control
- PID speed control
- Position control by feedforward controller
- Position control by internal model controller

This experiment as a pioneer experiment in our laboratory has been applied in the spring semesters of year 2001-02 and year 2002-03 in the undergraduate control course"ACE3010 Modern Control Systems Analysis and Design". The details will be discussed in Chapter 7.

2.2 Coupled Tank System

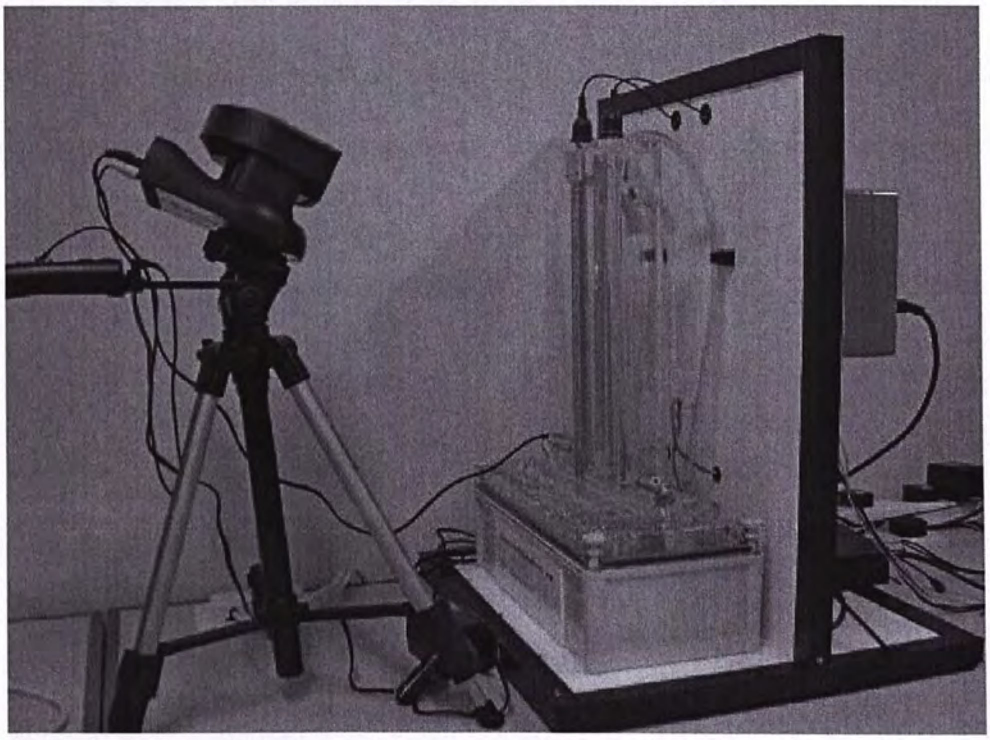

Figure 2.4 Coupled Tank Setup

This experiment is designed to test how various controllers perform when used to maintain water levels of two tanks coupled at the bottom. Figure 2.4 and Figure 2.5 show the coupled tank apparatus and the interface for this experiment, respectively.

The coupled tank control apparatus consists of two small Perspex tower-type tanks mounted above a reservoir which functions as storage for the water. Water is pumped into the top of each tank by two independent pumps. The head of water in each may be visually read on the attached scale at the front of the tanks. Each tank is fitted with an outlet, at the side near the base, and this outlet is connected through a plastic hose to the reservoir. The amount of water which returns to the reservoir is approximately proportional to the head of water in the tank since the plastic water-return tube at the base of the tank functions as a pseudo-linear hydraulic resistance. A screw clamp valve is provided on the tubing to increase this resistance. The level of water in each tank is monitored by a capacitive-type probe, which in conjunction with electronic circuits in the box at the rear of the unit provides an output signal proportional to the water level. This experiment includes three parts.

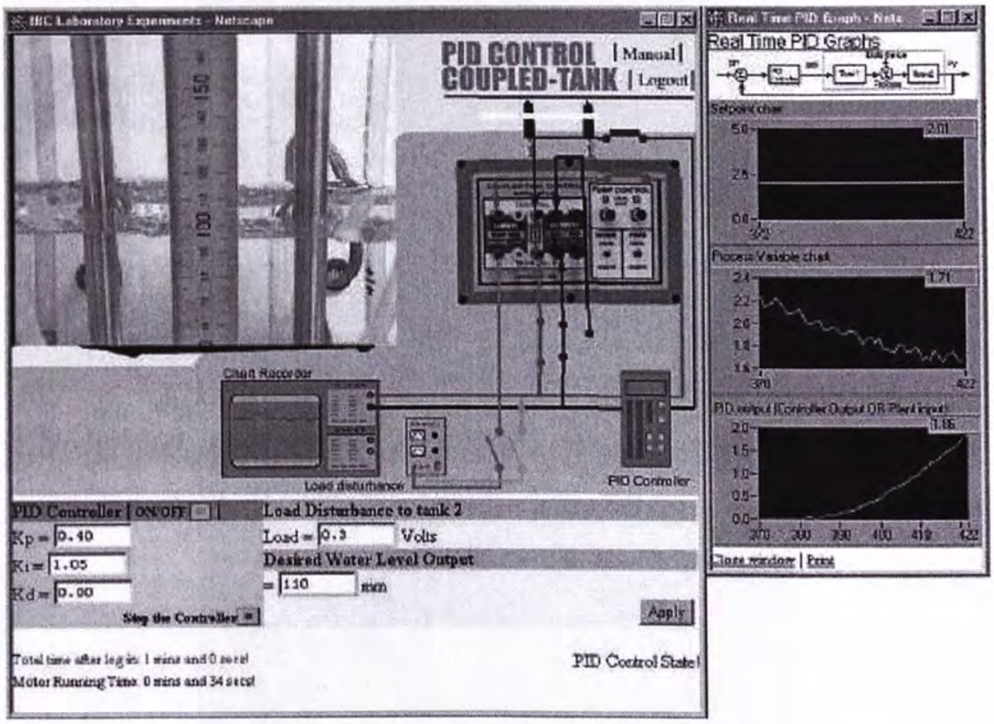

Figure 2.5 Coupled Tank Experiment Interface

- **Open loop (manual) control**

This part aims to observe the performance and limitation of open loop control (manual control) for set point change and for disturbance rejection.

- **Feedback control**

The objective of this part is to study the transient and steady state performance of the coupled tank apparatus under proportional feedback control.

- **Tuning a PID controller**

This part requests users to tune a PID controller using Ziegler-Nichols tuning rules to examine each term of the PID controller and its effect on the open-loop and closed-loop system response.

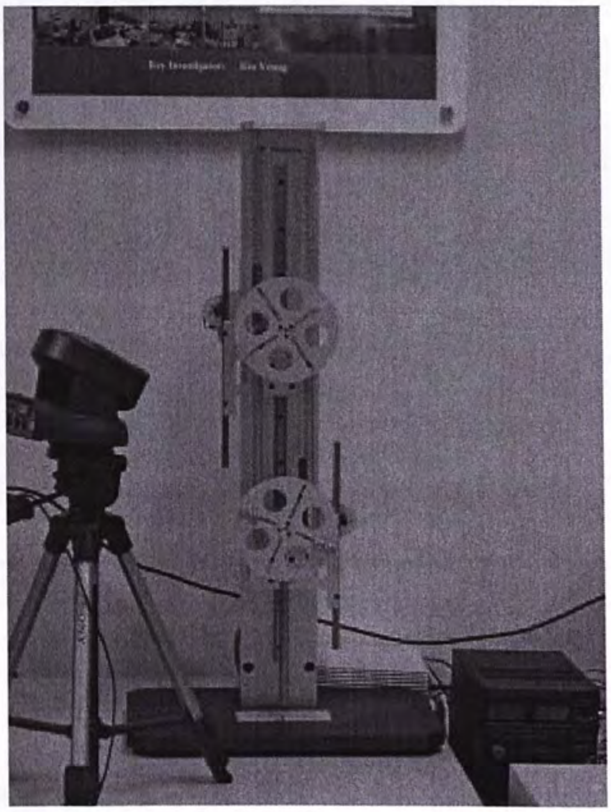

Figure 2.6 Mass-Spring-Damper Setup

2.3 Mass-Spring-Damper System

The mass-spring-damper system is one of the most common plants in control experiment education. In the department of ACAE, CUHK, an experiment on the same set of apparatus is offered in the course "ACE2810 Laboratory II" for the year 2 undergraduate students. This web-based experiment is established to allow students conduct the actual experiment on their own schedule through the Internet. It can also apply to part-time MSC courses.

Figure 2.6 and Figure 2.7 show the setup of the mass-spring-damper system and the interface for the experiment, respectively. The objective of this experiment is to study frequency response on an electromechanical system by mean of Bode plots, and to model the system.

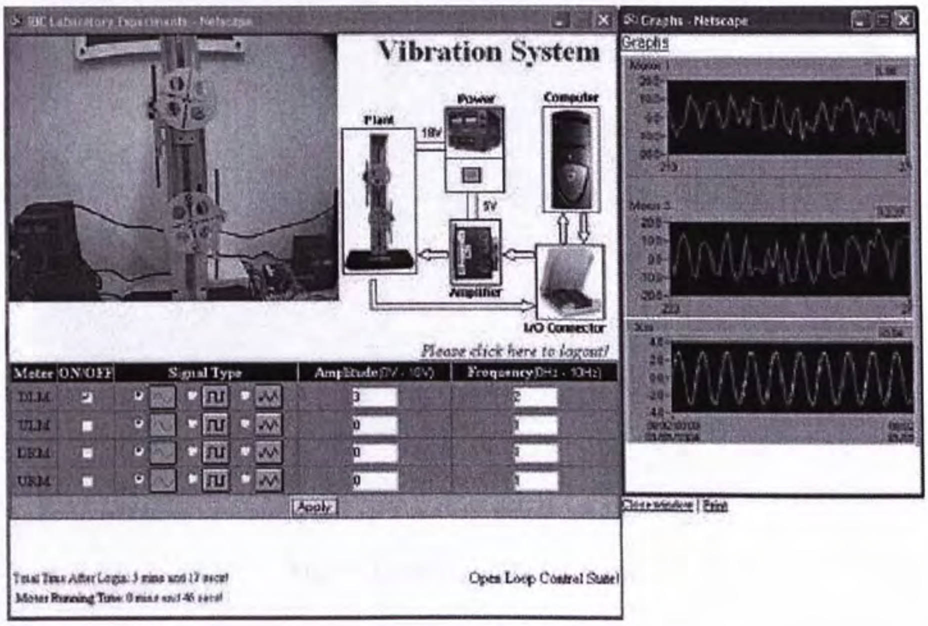

Figure 2.7 Mass-Spring-Damper Experiment Interface

The experiment setup consists of the instruments such as a Phimatic vibration system, DC Brush Servo Amplifier, I/O Connector, and so on. The Phimatic vibration system (MIMO123) is a training system designed to help students to learn vibration and control system. It features a coupled mass-spring-damper system. A 4-channel DC servo amplifier drives the actuators on MIMO123. The positions of the masses are made available by encoders mounted in the system.

The experiment is designed to apply all kinds of inputs with different amplitudes and frequencies on some of the four motors, and then record the response. From response behaviors, user can better understand the model of a coupled mass-spring-damper system. More details will be given in Chapter 5.

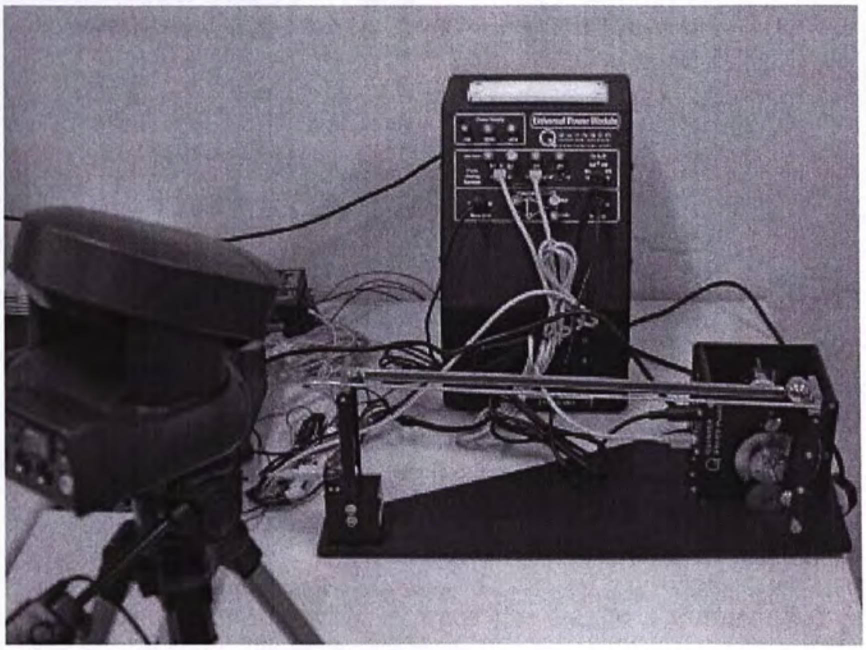

Figure 2.8 Ball and Beam Setup

2.4 Ball and Beam System

The ball and beam system is one of the most popular and important laboratory models for teaching control system engineering. Figure 2.8 and Figure 2.9 show the ball and beam module and the interface for this experiment.

A DC motor drives a beam such that the motor angle controls the tilt angle of the beam. A ball travels along the length of the beam. When the beam is horizontal, the ball does not experience any acceleration. The ball position is measured using a conductive plastic element mounted on the beam. An optional remote sensor is also available for operation in master/slave tracking mode.

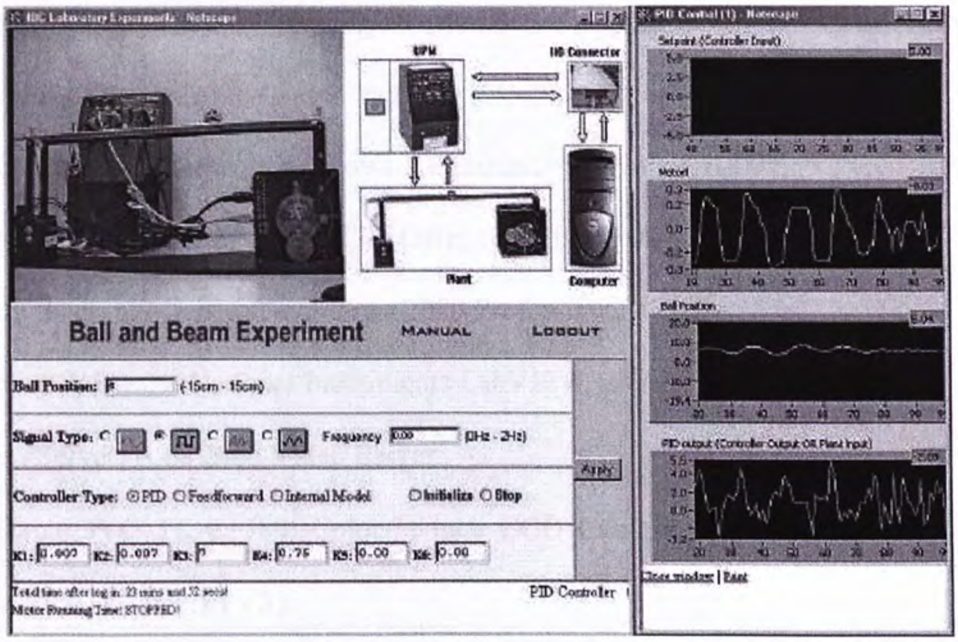

Figure 2.9 Ball and Beam Experiment Interface

The aim is to design a control system to track the ball to a commanded position. The system is supplied with several of controllers for the servo as well as the ball position.

We have designed three sets of controllers for this system. They are:

- PD controller
- Feedforward controller
- Internal model controller

2.5 Configurations

- Web Server:

Computer: Intel Pentium III CPU Family 6 Model 8 Stepping 6 860.946MHz ($\times 2$); 1.00GB of RAM.

Operation System: Red Hat 7.0 Linux with Apache web server.

- Controller Server

Computer 1: Intel x86 CPU Family 6 Model 8 Stepping 6 AT/AT COMPATIABLE; 256MB of RAM.

Operation System: Microsoft Windows XP Professional Version 2002.

Computer 2: Intel Pentium 4 CPU 3.06 GHz; 1.00GB of RAM.

Operation System: Microsoft Windows 2000 Professional Version.

Application Software: National Instruments LabVIEW 6.0.

- Video Server: Axis 2400 Video Server.
- Cameras: JVC TK-C1380, Color ½-Inch CCD Camera; SONY EVI-D30 AF (Auto Focus) CCD Camera ($\times 3$).
- Power Suppliers: 0-30V, 2.5A, DC Regulated Power Supply EP-611 ($\times 4$).
- DAQ Card:

NI PCI-6036E: 200 kS/s, 16-Bit, 16 Analog Input Multifunction DAQ ($\times 2$).

NI PCI-6703: 16-Bit High-Resolution Analog Source, 16 Voltage Outputs, 8 Digital I/O Lines.

- DC Motor Control Module.
- Coupled-Tank Control Apparatus PP-100 (KentRidge Instruments Pte Ltd).
- Phimatic Vibration System.
- DC Brush Servo Amplifier (Model 403).
- I/O Connector (SCB-68).
- Quanser Rotary Servo Plant with Encoder (SRV02-E-T).
- Quanser Ball and Beam Sensor (BB01).
- Quanser Universal Power Module (UPM1503).

Chapter 3

System Architecture

The web-based laboratory consists of various sets of experiment systems illustrated in the last chapter. Essentially, each system shares the same architecture. The main objective of an experiment system is to apply all kinds of commands to the specified plant and record the responses. To this end, the system should have three basic functions. One is to receive the user's command at any remote terminal and transfer the command through Internet to local plant. The second function is to collect the responses of the plant and transfer the data to user's terminal in opposite direction. Additionally, to construct the virtual environment of the experiment field for the user, the system needs to transfer the real time video to remote browser. To realize these functions, the system architecture should be properly designed. In this section, we will discuss the system architecture including both hardware and software in details.

3.1 Hardware Architecture

The overall hardware architecture of the system is shown as in Figure 3.1 via the mass-spring-damper system, which consists of a server machine acting as web server, a PC acting as controller server (also called LabVIEW server), and a video server linked with a CCD (Charge-Coupled Device) camera. A hub is used to connect the Internet accessible gateway, the servers, and other PCs in this Internet network called as Intranet. Basically, the web server is the gate from external Internet through Intranet to the local plant, while the controller PC controls the application system through a Data Acquisition (DAQ) interface card. The video server linked with the CCD camera transfers the real time video signal so that remote users can monitor the operations of the experiments in real time.

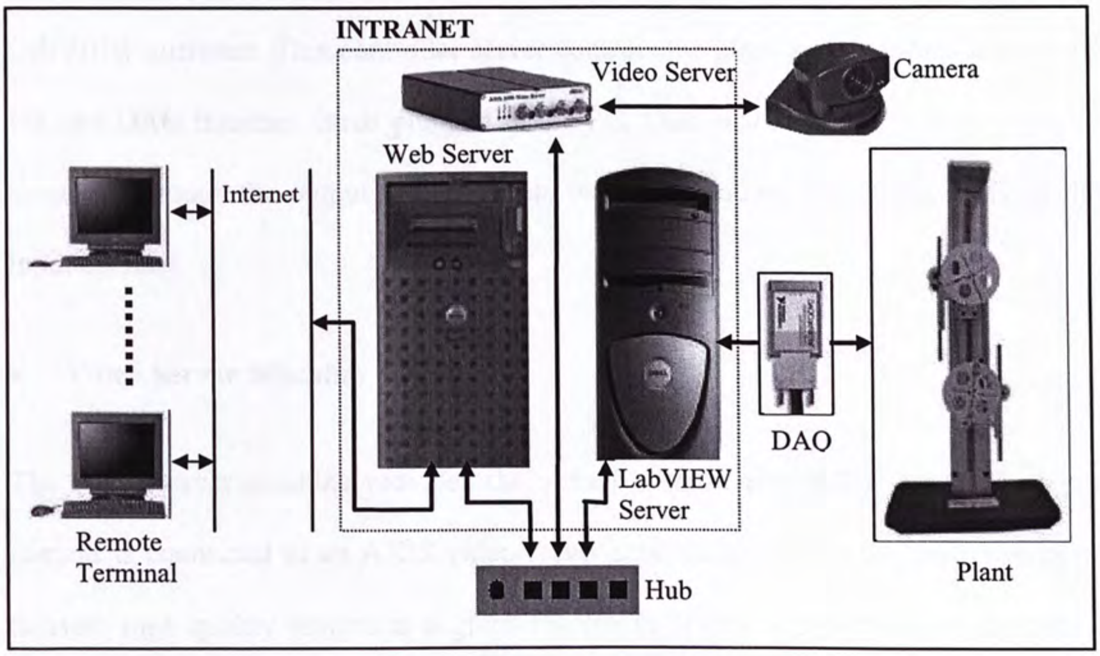

Figure 3.1 Hardware Architecture

The dashed line box in Figure 3.1 contains three major devices which form an internal network called Intranet described as follows.

- **Web Server Machine**

The web server machine serves as a gateway from internal network to Internet and prevents a direct connection of the controller PC to the Internet. This server machine and the controller PC form an internal system, which can be signed with virtual IP address known only by this server machine. This security feature is used for preventing unauthorized users from intruding the controller PC.

- **LabVIEW Server Machine**

The LabVIEW server machine acts as the bridge between the Intranet system and the plant. Facing the application system (plant), it is indeed the controller PC, which runs the LabVIEW software. This controller server controls the plant and measures the plant states via two DAQ interface cards plugged in the PC. One card sends the control signal to the actuators through the output channel while the other acquires the feedback signal through input channel.

- **Video Server Machine**

The video server machine provides the virtual environment. SONY or JVC color CCD camera is connected to an AXIS video server module to capture the real time images. It delivers high quality images at a given resolution of 352×288 pixels in standard JPEG (Joint Photographic Experts Group) format at a rate of 25 frames per second. The delay on the video frames depends largely on the band-width of the user's network. Our server in the lab is currently in a 100-Mbit subnet with typical inter-network communication rates up to 1Mbytes/s. The subnet is connected to the Gigabit Ethernet backbone network through ATM edge devices in the main campus. Thus, bandwidth is not a constraint for the implementation of remote laboratory experimentation within campus. The performance is satisfactory for students to view the video locally.

3.2 Software Architecture

The software architecture shown in Figure 3.2 is mainly composed of three parts, the client, the Apache web server, and the controller PC. They are connected by TCP/IP or TCP connection. All networking algorithms are based on client/server structure.

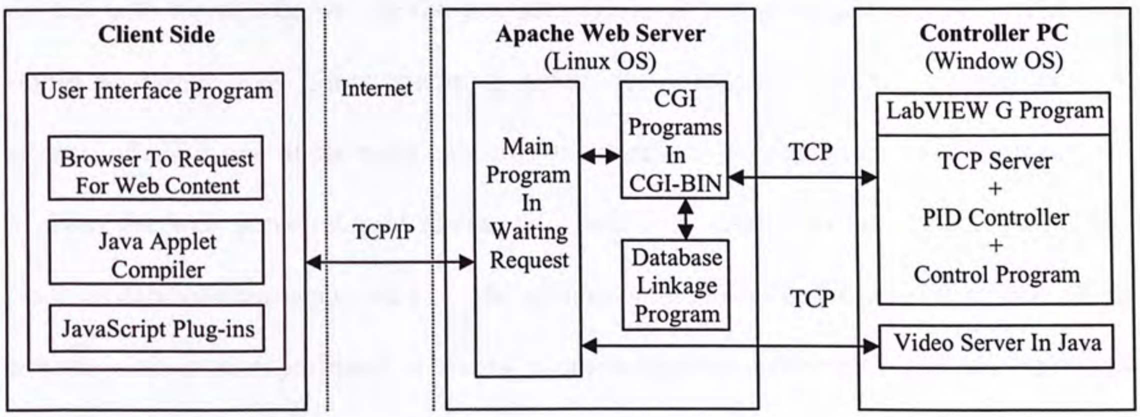

Figure 3.2 Software Architecture

- **Client Side**

On the client side, Java Applets and JavaScript embedded in HTML (Hypertext Markup Language) files are used to run on the client machine to provide a user friendly interface, which provides the related introduction about the experiment, i.e., system description, system theory, apparatus figure, performance manuals, and so on.

HTML is the basic format to provide a simple page on web browsers. Web writers today face significant challenges on making their web pages interactive. The static nature of HTML limits its creative choices, and interactive components are difficult to build and reuse. However JavaScript enhances and extends the interactive ability of web programming technique. It is a lightweight object-based scripting language complementing the dynamic way of what HTML often lacks. We use JavaScript on such jobs as maintaining a count down clock, changing pictures, resizing windows, displaying video layer, and browser checking. JavaScript makes our experiment interface much more lively.

- **Apache Web Sever**

On the web server side we use the free integration of "Linux+Apache+PHP". The highly stable performance of Linux operating system can greatly enhance the stability of overall system, which is one of the main concerns of a user who is conducting an experiment.

Mainly, the web server should realize two functions. One is to use DB-file packages to perform database management. i.e., user authorization, user conflict checking, controlling a user to perform an experiment or several users to perform different experiments at one time, and limitation of related performance time. Each time a user inputs the parameters, the system can update these parameters in his/her database.

The other function is realization of communication between client side and controller PC. The web server needs to transfer the experiment parameters from client side to controller PC, and feedback the experiment result from controller PC to client side. So we can say the web server acts as the doubled roles of client and server. Thus, it is necessary to construct two kinds of sockets in the web server programs to call the primary client and server socket functions, respectively, to finally realize the communication between client side and controller PC. In the web server, we use CGI programs. CGI is a standard for setting up interaction between external application and information severs. All CGI in the web server are written in PERL language, which is the most popular and powerful way to handle CGI.

- **Controller PC**

The function of controller is listening, collecting experiment parameters, and controlling the plant. When the plant is ready, controller PC begins to collect, analysis, and process signals, and then sends the result to the web server, finally to the client side. On the controller PC side we use LabVIEW G language. LabVIEW (Laboratory Virtual Instrument Engineering Workbench) is a revolutionary graphical development environment with built-in functionality for data acquisition, instrument control, measurement analysis, and data presentation. It gives users the flexibility of a powerful programming language without the complexity of traditional development environments. LabVIEW supports network communication protocol, such as TCP, UDP, and it provides completed functional templates for programmer.

- **Program flow**

The programs in client side and web server are integrated, and physically, they are all stored in the web server machine. Only when some user accesses the web server from a remote browser, the client side program is downloaded and executed in the remote browser, the acute client machine. In Figure 3.3, the solid lines describe the program flow in the client side and web server, and the dotted lines describe the inheritance relationship of the windows.

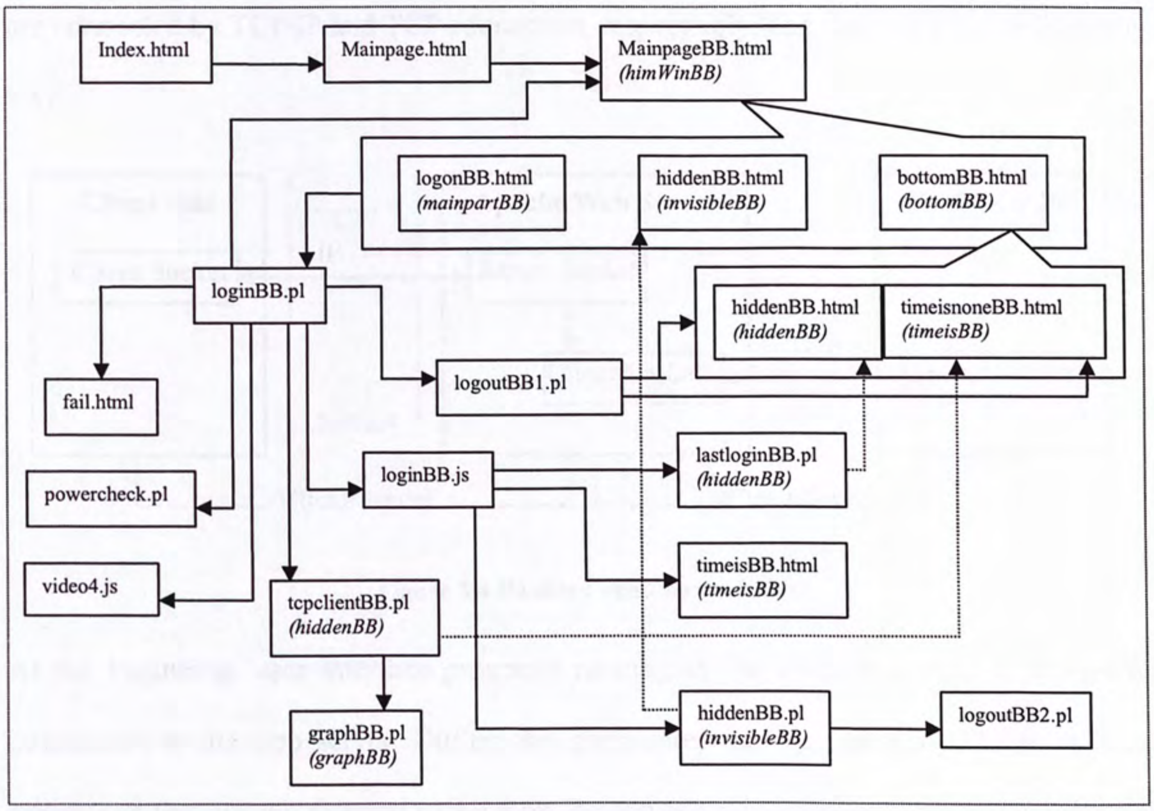

Figure 3.3 Program Flow

3.3 Architecture Characteristics

In this section, we will investigate some main architecture characteristics employed in the web-based laboratory.

- **Double Client/Server Pairs**

From Figure 3.4, which is abstracted from Figure 3.2, we can see that the whole software system essentially consists of two pairs of client/server structure. The first one is the client/web server pair and the second one is the web server/controller pair. These two pairs are connected by TCP/IP and TCP connection, respectively, and they work in the following way.

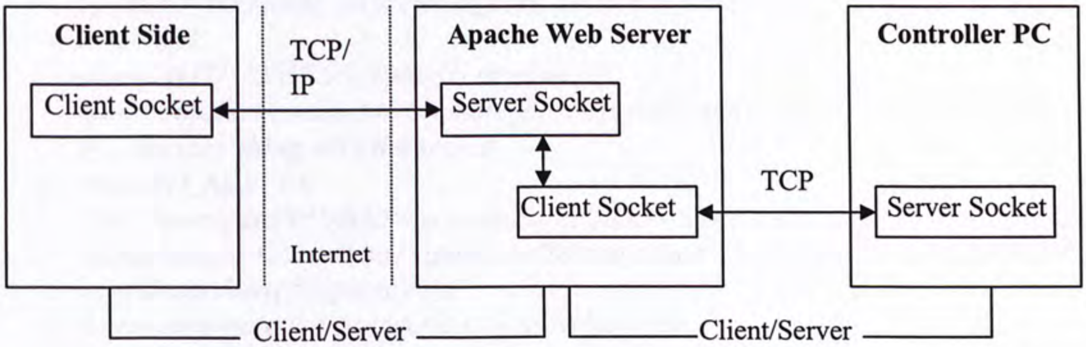

Figure 3.4 Double Client/Server Pairs

At the beginning, user interface programs running in the client side send a request for connection to the web server. During this procedure, the user agent/web browser is the client, and the Apache daemon running on the server machine is the server. Next, the web server transmits the commands to the controller PC by sending a request for connection to the LabVIEW TCP Vi programs (see Figure 3.5 for the code of "request for connection"). At this moment, the server becomes a client simultaneously, and the controller daemon in PC serves as a server. Therefore the web server performs two roles, namely, a server to the client side, and a client to the controller. To establish client/server application, we must create a socket pair with specified local IP address, local TCP port, remote IP address, and remote TCP port. A socket pair uniquely identifies every TCP connection on the Internet. The following code presents how to build the connection between web server and controller PC.

```
sub connectionDE {
        $remote_host = "XXXX.acae.cuhk.edu.hk";
        $remote_port = XXXX;
        # create a socket
```

```
socket(TO_SERVER, PF_INET, SOCK_STREAM, getprotobyname('tcp'));
# build the address of the remote machine
$internet_addr = inet_aton($remote_host) or return 0;
#die "Couldn't convert $remote_host into an Internet address: $!\n";
$paddr = sockaddr_in($remote_port, $internet_addr);
# connect
connect(TO_SERVER, $paddr) or return 0;
#die "Couldn't connect to $remote_host:$remote_port : $!\n";
# ... do something with the socket
print TO_SERVER
"k1=$userdata{'k1'}&k2=$userdata{'k2'}&k3=$userdata{'k3'}&k4=$userdata{'k4'
}&signaltype=$userdata{'signaltype'}&amplitude=$userdata{'amplitude'}&freque
ncy=$userdata{'frequency'}\n";
# and terminate the connection when we're done
close(TO_SERVER);
return 1;}
```

Figure 3.5 Code of "Request For Connection"

- **Extensible Structure**

In this chapter, the hardware and software architectures have be discussed. And it can be seen that each set of system, DC motor, coupled tank, etc, shares the same elemental architecture. In other words, the architecture is independent of the experiment plant. This structure allows us to develop new systems or design new experiments in the laboratory easily.

- **Independent Experiments**

To save the resources of hardware, e.g., computer, DAQ card, and software, e.g. LabVIEW license, it is reasonable and possible to use one PC to serve as the controller server for more than one set of systems. In the laboratory, there are two PCs serving for four sets of systems, in particular, one for DC motor system and coupled tank system, and the other for mass-spring-damper system and ball and beam system. On the other hand, at the application level, all experiments are independent, which means, all the experiments can be conducted by different users simultaneously. To achieve this objective, each system is allotted independent resources, such as, database, TCP connection, video channel, and so on.

Chapter 4

Control Methodology

Control is defined as the utilization of algorithms and feedback in engineered systems. And it plays an essential role in the development of technologies such as power, manufacturing, transportation and so on. Principle of control is the foundation to establish a control laboratory. In this chapter, we will give an overview of some important control ideas, various controller design methods, that will be used to design our experiment in the subsequent chapters.

4.1 Basic Control Concepts

Roughly, the objective of control is to force a system to behave in a desired manner. For example, the thermostat controlling room temperature is a typical control behavior with a feedback mechanism. Sometimes it is also desired to optimize the system performance, or minimize control costs.

In literatures, a typical control definition can be summarized by saying that one seeks to influence a dynamical system in order to achieve some desired goal. The dynamical system in control theory is usually a system of differential or difference equations that depend on a set of parameters, where the parameters are the control variables. The idea then is to find these control variables so as to minimize (or maximize) a given objective function, to stabilize the system, or to move the system to a desired destination.

Two kinds of control were defined and illustrated. In open-loop control, the system does not measure the output, and there is no compensation of the output to make it conform to the desired output. In closed-loop control, the system uses feedback, which is the process of measuring a control variable and returning the output to influence the value of the variable. The fundamental difference between the open-loop and close-loop systems is the feedback action, which has been the foundation for control system analysis and design.

A typical feedback control system shown in Figure 4.1 consists of the plant, output sensor, actuator, and controller.

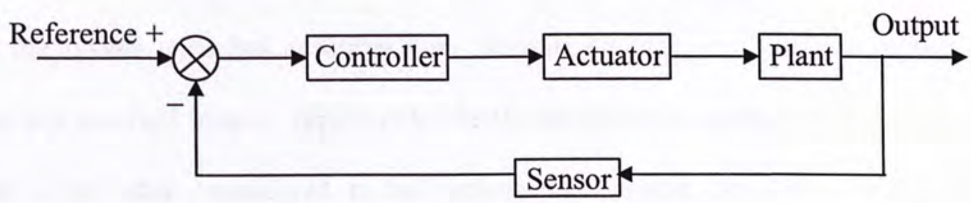

Figure 4.1 Component Block Diagram of a Feedback Control System

The central component of a control system is the plant (or called process), one of whose output variables is to be controlled. The sensor is used to acquire the output feedback, and the actuator is the device that can influence the controlled variable of the process. The controller determines how to influence the process.

The controller design methods can be chronologically classified by classical control methods that use complex variables, and modern control methods that rely on ordinary differential equations. In particular, in this chapter, we will introduce some particular controller design methods, including PID control, pole placement, feedforward control, and internal model control.

4.2 System Modeling

In analyzing a system and designing a controller, the first step is to develop a dynamic model that describes the behavior of the system. Basically, a completed system model can be expressed by a set of four elements as follows.

Model = (state, dynamics, input, output).

A key concept in modeling is the concept of state, and the state is a set of independent physical quantities, the specification of which (in the absence of excitation) completely determines the future evolution of the system. The dynamics of a model is an update rule for the system state that describes how the state evolves, as a function on the current state and any external inputs. Inputs describe the external excitation of the dynamics. Constant inputs are often considered to be parameters. Outputs describe the directly measured variables, which is a function of the state and inputs and is not independent variables. Not all states are outputs since some states can't be directly measured.

Among the modeling methods to be introduced below, the state space method precisely described the plant in the form of the four-element set. However, the classical transfer function method, in general, gives only part description of the plant in the sense that not all states are specified.

4.2.1 Analytical Model

For simple systems, it is precise and convenient to model them analytically. There are three typical ways to model a system. They are the higher order differential equations, the transfer function and the state space equations.

- Differential Equations

In many cases the modeling of complex systems is difficult and expensive. However, for the most common physical systems, there are basic principles of modeling. For example, the cornerstone for obtaining a mathematical model for any mechanical system is Newton's law. The basic equations of electric circuits are given by Kirchhoff's laws. In modeling temperature control systems involving the flow and storage of heat energy, the important principle is that heat energy flows through substances at a rate proportional to the temperature difference across the substance.

Basically, by using these physical principles, the mechanical systems, electrical systems, or heat flow systems, etc, can be modeled in the form of the differential equation as follows,

$$f\left(\frac{d^n y(t)}{dt^n},\frac{d^{(n-1)}y(t)}{dt^{(n-1)}},\cdots\frac{dy(t)}{dt},y(t),\frac{d^n u(t)}{dt^n},\frac{d^{(n-1)}u(t)}{dt^{(n-1)}},\cdots,\frac{du(t)}{dt},u(t)\right)=0 \tag{4.1}$$

where $u(t)$ and $y(t)$ are the input and output of the system, respectively. A system modeled by (4.1) is called a linear system if the function f is linear, in particular, the system can be rewritten by

$$\begin{aligned}&\frac{d^n y(t)}{dt^n}+a_1\frac{d^{(n-1)}y(t)}{dt^{(n-1)}}+\cdots+a_{n-1}\frac{dy(t)}{dt}+a_n y(t)\\&=b_0\frac{d^n u(t)}{dt^n}+b_1\frac{d^{(n-1)}u(t)}{dt^{(n-1)}}+\cdots+b_{n-1}\frac{du(t)}{dt}+b_n u(t)\,,\ a_1,\ldots,a_n,b_0,b_1,\ldots,b_n\in R.\end{aligned} \tag{4.2}$$

- Transfer Function

By applying the Laplace transform on both sides of a linear system (4.2), we can obtain the transfer function of the system as follows,

$$P(s)=\frac{Y(s)}{U(s)}=\frac{b_0 s^n+b_1 s^{n-1}+\cdots+b_{n-1}s+b_n}{s^n+a_1 s^{n-1}+\cdots+a_{n-1}s+a_n} \tag{4.3}$$

where $Y(s) = L\{y(t)\}$, $U(s) = L\{u(t)\}$. In this chapter, we suppose the transfer function is strictly proper, that is, $b_0 = 0$ in (4.3). Denote the zeros of (4.3) by $z_i, i = 1, \cdots m,$ for some integer $m < n$, and the poles of (4.3) by p_i, $i = 1, \cdots n,$ that is, $b_1 z_i^{n-1} + \cdots + b_{n-1} z_i + b_n = 0$ and $p_i^n + a_1 p_i^{n-1} + \cdots + a_{n-1} p_i + a_n = 0$. The stability criterion of a system modeled by (4.3) is that all poles p_i, $i = 1, \cdots n,$ have negative real parts.

- State Space Equations

Differential equations can be expressed as a set of simultaneous first-order differential equations. These are represented in the state variable form as the vector equation as follows.

$$\begin{aligned} \dot{x} &= f(x,u) & x &\in R^n \\ y &= h(x,u) & u &\in R, y \in R. \end{aligned} \tag{4.4}$$

And the linear system can be rewritten as

$$\begin{aligned} \dot{x} &= Fx + Gu, & F &\in R^{n \times n},\ G \in R^{n \times 1} \\ y &= Hx + Ju, & H &\in R^{1 \times n},\ J \in R^{1 \times 1}. \end{aligned} \tag{4.5}$$

The stability criterion of a system modeled by (4.5) is $\mathrm{Re}(\lambda) < 0$, where λ is the eigenvalue of F, i.e., $\det(\lambda I - F) = 0$. The transfer function of (4.5) can be calculated as follows,

$$H(sI - F)^{-1} G + J = P(s). \tag{4.6}$$

If a system with transfer function (4.3) is related to (4.5) by equation (4.6), then (4.5) is said to be a realization of (4.3). For a transfer function, there are many kinds of realizations. In particular, there are two canonical forms. One is the control canonical form realization, where

$$F=\begin{bmatrix} -a_1 & -a_2 & \cdots & -a_{n-1} & -a_n \\ 1 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \cdots & \vdots & \vdots \\ 0 & 0 & & 0 & 0 \\ 0 & 0 & \cdots & 1 & 0 \end{bmatrix} = \begin{bmatrix} -a_1 \cdots -a_{n-1} & -a_n \\ I_{n-1} & 0_{(n-1)\times 1} \end{bmatrix} = A_c$$

$$G=\begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix} = B_c, H=\begin{bmatrix} b_1 & b_2 & \cdots & b_n \end{bmatrix} = C_c, J=0=D_c,$$

and $C_c(SI-A_c)^{-1}B_c = \dfrac{b_1 s^{n-1}+\cdots+b_{n-1}s+b_n}{s^n+a_1 s^{n-1}+\cdots+a_{n-1}s+a_n} = P(s)$. The other is the observer canonical form realization, where

$$F=\begin{bmatrix} -a_1 & 1 & 0 & \cdots & 0 \\ -a_2 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ -a_{n-1} & 0 & 0 & \cdots & 1 \\ -a_n & 0 & 0 & \cdots & 0 \end{bmatrix} = \begin{bmatrix} -a_1 & \\ \vdots & I_{n-1} \\ -a_{n-1} & \\ -a_n & 0_{1\times(n-1)} \end{bmatrix} = A_o = A_c^T$$

$$G=\begin{bmatrix} b_1 \\ \vdots \\ b_n \end{bmatrix} = B_o = C_c^{\,T}, H=\begin{bmatrix} 1 & 0 & \cdots & 0 \end{bmatrix} = C_o = B_c^T, J=0=D_o,$$

and $C_o(SI-A_o)^{-1}B_o = \dfrac{b_1 s^{n-1}+\cdots+b_{n-1}s+b_n}{s^n+a_1 s^{n-1}+\cdots+a_{n-1}s+a_n} = P(s)$.

4.2.2 Experimental Model

In many cases, it is impossible to exactly model a system only by mathematical induction. Modeling a system from the experiment data is another important method. Next, we will consider this method for a second order linear system.

The basic idea is to apply different inputs on the plant, then collect the outputs. A second order linear system can be modeled from the input-output pairs. The system output under certain input is also called system response. One of the most important responses for a linear system is the so-called frequency response, which describes how a linear system responds to sinusoidal inputs and how this response can be obtained from its pole and zero locations. The frequency response is a unique character for linear system.

It is relatively easy to obtain the frequency response of a system experimentally. On the frequency response data, which result from exciting the system with sinusoidal inputs at many different frequencies, the Bode plots can be achieved. Bode plots method is the most useful technique developed by H. W. Bode at Bell Laboratory between 1932 and 1942.

The remaining problem is how to obtain the transfer function, i.e., the pole-zero model from the Bode plots. In fact, it is a well known technique in classical control theory. Here, we will give an example which will also be helpful in the next chapter.

A typical second order transfer function is represented by

$$P(s) = \frac{K(s/w_1 + 1)}{(s/w_n)^2 + 2\xi s/w_n + 1} \tag{4.7}$$

and the frequency response is plotted by Figure 4.2.

From Figure 4.2, it is ready to measure $w_1 \cong 2.0$ rad/sec and $20\log K \cong 9.55$, hence $K \cong 3.0$, where w_1 is the frequency at which the two magnitude asymptotes intersect, and K is the magnitude when the frequency is sufficiently small.

Then plot the Bode plots for $3.0(s/2.0+1)$ as Figure 4.3.

Because of the property that Bode plots of systems in series simple add, which is quite convenient, the Bode plots of $\frac{1}{(s/w_n)^2 + 2\xi s/w_n + 1}$ can be achieved by subtracting Figure 4.3 from Figure 4.2. And the result is shown in Figure 4.4.

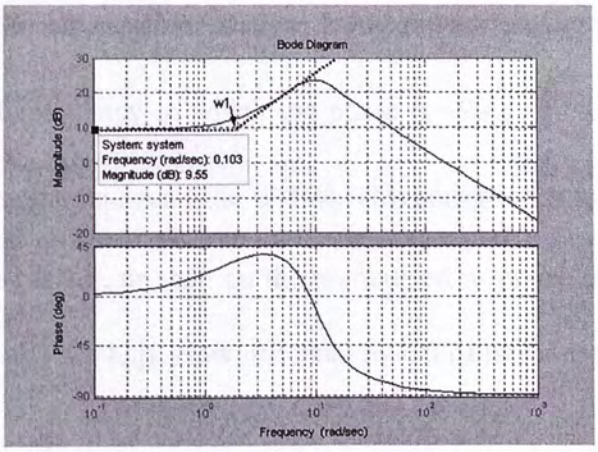

Figure 4.2 Bode Diagram of System (4.7)

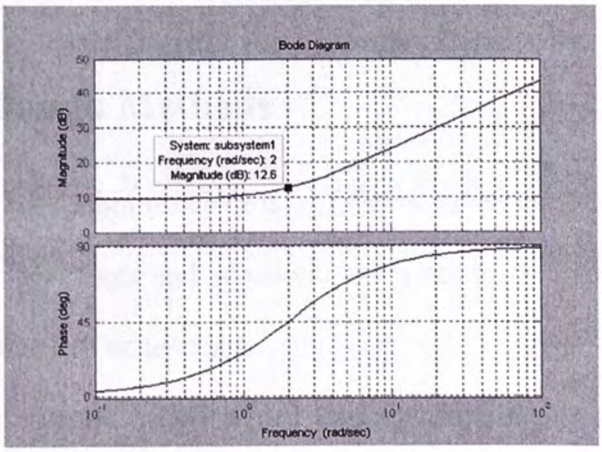

Figure 4.3 Bode Diagram of Subsystem $3.0(s/2.0+1)$

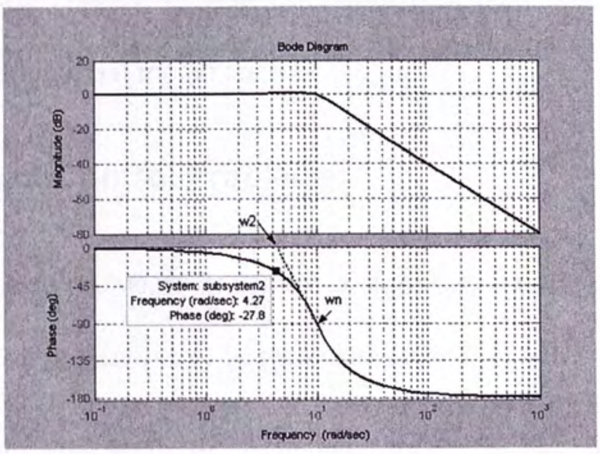

Figure 4.4 Bode Diagram of Subsystem $1/\left[(s/w_n)^2+2\xi s/w_n+1\right]$

From Figure 4.4, it can be measured that $w_n \cong 10.0$ rad/sec and $w_2 \cong 4.27$ rad/sec, where w_n is the break point frequency at which the phase is -90°, and w_2 is the frequency at which the phase asymptote intersects the 0° line. This corresponds to $w_n / w_2 \cong 2.35$, which in turn corresponds to $\xi \cong 0.5$, as seen on the normalized response curves of second order system (see Figure 6.2(b) of [11]). Now, the final model of transfer function (4.7) is given by

$$P(s) = \frac{3.0(s/2.0+1)}{(s/10.0)^2 + s/10.0+1}.$$

4.3 Controller Design Methods

In general, the controller design problem is as follows, given a model of the system to be controlled (including its sensors and actuators) and a set of design goals, find a suitable control law, or determine that none exists.

In our web-based laboratory, we designed various experiments ranging from system modeling such as frequency response and Bode plots, frequency design methods such as PID control and lead-lag control, to state space design methods such as pole placement, feedforward control and internal model control.

4.3.1 Formulation of Control Problems

There are two elementary problems in control design, i.e., stabilization and tracking. For linear systems, these two problems can be formulated below.

Stabilization: Given equilibrium point $x_e \in R^n$, find control law $\begin{cases} u = k(x,z) \\ \dot{z} = \gamma(z,y),\ z \in R^{n_z} \end{cases}$, such that the closed-loop system is stable, that is,

$$\lim_{t\to\infty} x(t) = x_e,\ \lim_{t\to\infty} z(t) = 0,\ \textit{for all}\ x(0) \in R^n, z(0) \in R^{n_z}.$$

Tracking: Given $y_d(t) \in R$, find $\begin{cases} u = k(x,z,y_d) \\ \dot{z} = \gamma(z,y,y_d),\ z \in R^{n_z} \end{cases}$, such that $\begin{cases} u = k(x,z,0) \\ \dot{z} = \gamma(z,y,0) \end{cases}$ stabilize the equilibrium point, and $\lim_{k\to\infty}(y(t) - y_d(t)) = 0$ for all $x(0) \in R^n, z(0) \in R^{n_z}$.

Next, we will discuss various control methods one by one.

4.3.2 PID Controller

Consider the tracking problem, with $y_d(t) = r, t \geq 0$, where r is a constant. A typical PID controller is

$$u = K_p e + K_i \int e dt + K_d \frac{de}{dt}, \tag{4.8}$$

where $e = r - y$ is the tracking error, and K_p, K_i, K_d are proportional (P), integral (I), and derivative (D) gains, respectively. The controller transfer function is given by $D(s) = K_p + \frac{K_i}{s} + K_d s$.

The closed-loop system under the PID controller is described in Figure 4.5.

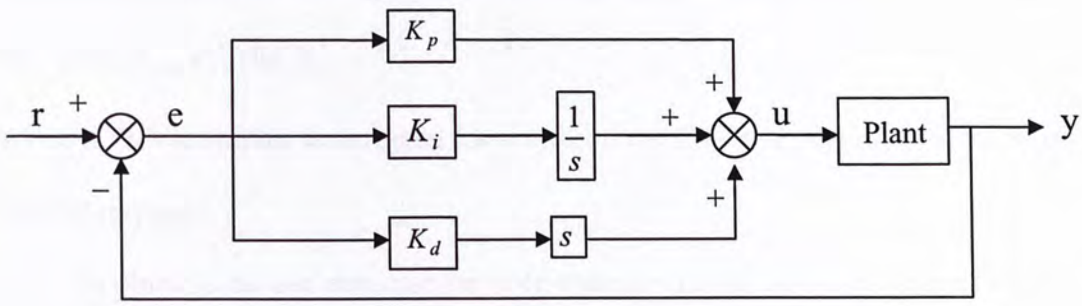

Figure 4.5 Block Diagram of the Closed-loop System under PID Controller

The P, I, and D terms of the PID controller have the characteristics below.

- Proportional term: provides inputs that correct current errors.
- Integral term: insures that steady state error goes to zero (if not, control gets bigger).
- Derivative term: provides anticipation of upcoming changes.

In performance, a proportional control (K_p) will reduce the rise time and reduce, but never eliminate the steady-state error. An integral control (K_i) will have the effect of eliminating the steady-state error, but it may make the transient response worse. A derivative control (K_d) will increase the stability of the system, reduce the overshoot, and improve the transient response. The effects on the transient response of a closed-loop system are summarized in the table shown below.

	RISE TIME	OVERSHOOT	SETTING TIME
K_p	Decrease	Increase	Small Change
K_i	Decrease	Increase	Increase
K_d	Small Change	Decrease	Decrease

Table 4.1 Effects of P, I, D on a Closed-loop System

However, these correlations may not be exactly accurate, because K_p, K_i, and K_d are dependent of each other. In fact, changing one of these variables can change the effect of the other two. For this reason, the table should only be used as a reference for determining the values K_p, K_i, and K_d.

When a PID controller is designed for a system, the following should be done to obtain a desired response.

1. To obtain a desired response for open-loop control of the system and determine what should be done to improve the system.
2. Then to improve the rise time by adding a proportional control.
3. Next to improve the percent overshoot by adding an integral control.
4. The steady-state error can be eliminated by adding an integral control.
5. Finally, adjust each of K_p, K_i, and K_d until the desired overall response is obtained.

In the designing of PID control, it is not necessary to implement all three terms (proportional, derivative, and integral) into a single controller. For example, if a PD controller gives a good enough response, then the implementation of integral controller to the system is not necessary. The design of the controller should be kept as simple as possible.

4.3.3 Pole Placement

Pole placement, as well as feedforward and internal model to be discussed later, is classified as state space approach, which is often referred to as modern control design. In state space design, the control engineer designs a dynamic compensation by working directly with the state variable description of the system.

The pole placement controller aims to the stabilization problem. Consider system modeled by state space equation (4.5), the pole placement controller is a controller of form

$$u = -Kx \tag{4.9}$$

such that $(F - GK)$ is stable, that is, $\mathrm{Re}(\lambda) < 0$ where λ is the eigenvalue of $(F - GK)$, i.e., $\det(\lambda I - (F - GK)) = 0$.

It is known there exits a pole placement controller if the pair (F, G) is stabilizable.

4.3.4 Feedforward Controller

The feedforward control aims to the tracking problem with desired output $y_d(t) = r, t \geq 0$.

Consider system (4.5), a feedfoward controller has the form of

$$u = -Kx + Mr, \tag{4.10}$$

such that

(a) $(F - GK)$ is stable;

(b) $\lim_{t \to \infty} (y(t) - r) = 0.$

The block diagram of the closed-loop system under feedforwad controller is shown in Figure 4.6.

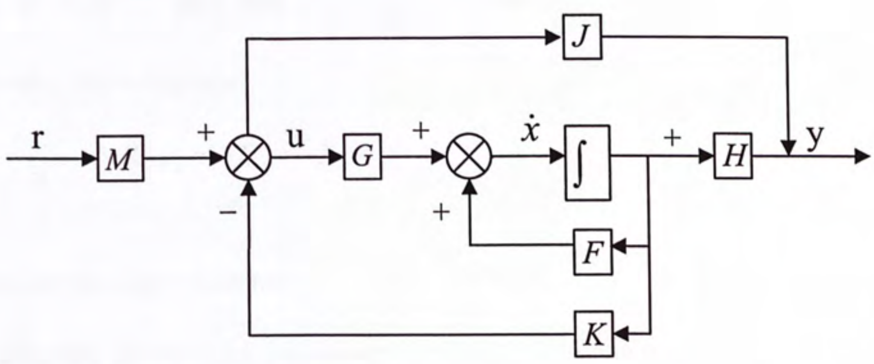

Figure 4.6 Block Diagram of the Closed-loop System under Feedforward Controller

There are two parameters K and M in the feedforward controller, which are calculated in the following way.

(i) Under the assumption that (F,G) is stabilizable, there exists $K \in R^{1\times n}$ such that $(F-GK)$ is stable.

(ii) Calculate $N_x \in R^{n\times 1}$ and $N_u \in R^{1\times 1}$ from $\begin{bmatrix} N_x \\ N_u \end{bmatrix} = \begin{bmatrix} F & G \\ H & J \end{bmatrix}^{-1} \begin{bmatrix} 0_{n\times 1} \\ 1 \end{bmatrix} \Leftrightarrow \begin{matrix} FN_x + GN_u = 0_{n\times 1} \\ HN_x + JN_u = 1 \end{matrix}$.

(iii) $M = N_u + KN_x$.

4.3.5 Internal Model Controller

The internal model is used also to deal with the tracking problem. Consider system (4.5) with $y = Hx$ and desired output $y_d(t) = r, t \geq 0$. The dynamics $\dot{z} = e = Hx - r$ is called the internal model of r. And the controller based on the internal model is designed as follows.

Step 1: Form an augmented plant $\begin{cases} \dot{x} = Fx + Gu \\ \dot{z} = Hx - r \end{cases}$. Letting $X_a = \begin{bmatrix} x \\ z \end{bmatrix}$ gives

$$\dot{X}_a = \begin{bmatrix} \dot{x} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} F & 0 \\ H & 0 \end{bmatrix} \begin{bmatrix} x \\ z \end{bmatrix} + \begin{bmatrix} G \\ 0 \end{bmatrix} u + \begin{bmatrix} 0 \\ -1 \end{bmatrix} r = F_a x_a + G_a u + G_r r.$$

Step 2: Find $K_a \in R^{1\times(1+n)}$ such that $(F_a - G_a K_a)$ is stable.

Step 3: Construct the controller

$$\begin{cases} u = -K_a x_a = -K_x x - K_z z \\ \dot{z} = e \end{cases} \quad \text{where } K_a = [K_a \quad K_z] \tag{4.11}$$

which solves the tracking problem.

The block diagram of the closed-loop system under internal model controller is shown in Figure 4.7.

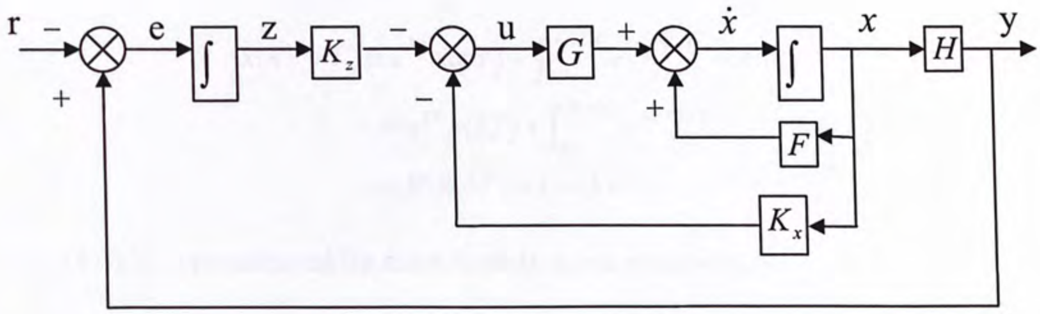

Figure 4.7 Diagram of the Closed-loop System under Internal Model Controller

4.4 Digital Control

All the controllers discussed so far are formulated in continuous time, which can be built using analog electronics. However, the control systems in our web-based laboratory use digital computers to implement the controllers. Now, we will show how to implement these controllers in a digital computer.

Unlike analog electronics, digital computers cannot integrate. Therefore, the differential equations must be approximated by difference equations involving addition and multiplication only. One particular simple way to obtain a difference equation from a differential equation is to use Euler's method. It resulted in the approximation

$$\dot{x}(t)\big|_{t=kT} \cong \frac{x(k+1)-x(k)}{T},$$

where $T = t_{k+1} - t_k$ =the sample interval in seconds, $t_k = kT$, k=an integer, $x(k)$= value of x at t_k, and $x(k+1)$= value of x at t_{k+1}.

To use the state space method, the first step is to digitize the state space equations. Consider continuous system (4.5), it is known its solution is

$$x(t) = e^{F(t-t_0)}x(t_0) + \int_{t_0}^{t} e^{F(t-\tau)}Gu(\tau)d\tau .$$

Letting $t=(k+1)T,\ t_0=kT$ gives

$$\begin{aligned}x(kT+T) &= e^{FT}x(kT)+\int_{KT}^{(K+1)T}e^{F(KT+T-\tau)}Gu(\tau)\\ &= e^{FT}x(kT)+\int_{KT}^{(K+1)T}e^{F(KT+T-\tau)}Gd\tau\, u(kT)\\ &= \Phi\, x(kT)+\Gamma\, u(kT).\end{aligned}$$

Thus, (4.5) is approximated by discrete state space equations

$$\begin{aligned}x(k+1) &= \Phi x(k)+\Gamma\, u(k)\\ y(k) &= H\, x(k)+J\, u(k)\end{aligned}. \tag{4.13}$$

where $\Phi\in R^{n\times n}$, $\Gamma\in R^{n\times m}$, $H=R^{p\times n}$, $J=R^{P\times m}$, and $\Phi=e^{FT}$, $\Gamma=\int_0^T e^{F\eta}d\eta G$.

The stability criterion of a system modeled by (4.13) is $|\lambda|<1$, where λ is the eigenvalue of Φ, i.e., $\det(\lambda I-\Phi)=0$.

In particular, by the approximation, all the controllers we have studied can be implemented in discrete time, and the details are given below.

- **PID Controller**

The PID controller (4.8) will be digitized with a sampling T which yields a discrete PID controller of the form,

$$u(k)=K_p e(k)+K_i T\sum_{j=0}^{k}e(k)+K_d\frac{e(k)-e(k-1)}{T},k=0,1,2,\ldots \tag{4.12}$$

- **Pole Placement**

The pole placement controller is designed by

$$u(k)=-Kx(k) \tag{4.14}$$

such that $(\Phi-\Gamma K)$ is stable.

- **Feedforward Controller**

The discrete time approximation for feedforward controller (4.10) is

$$u(k) = -Kx(k) + Mr, \tag{4.15}$$

where K is such that $(\Phi - \Gamma K)$ is stable and $M = N_u + KN_x$ with $N_u \in R^1$ and $N_x \in R^{n\times 1}$

satisfying $\begin{bmatrix} N_x \\ N_u \end{bmatrix} = \begin{bmatrix} \Phi - I & \Gamma \\ H & 0 \end{bmatrix}^{-1} \begin{bmatrix} 0_{n\times 1} \\ 1 \end{bmatrix}$.

- **Internal Model Controller**

The discrete time approximation for internal model controller (4.11) is

$$\begin{cases} u(k) = -K_x x(k) - K_z z(k) \\ z(k+1) = z(k) + Hx(k) - r \end{cases} \tag{4.16}$$

where $K_a = [K_a \quad K_z]$ is designed such that $(\Phi_a - \Gamma_a K_a)$ is stable, with $\Phi_a = \begin{bmatrix} \Phi & 0 \\ H & 1 \end{bmatrix}, \Gamma_a = \begin{bmatrix} \Gamma \\ 0 \end{bmatrix}$.

Chapter 5

Mass-Spring-Damper System

The mass-spring-damper system is one of the most common apparatus in control experiment education. The objective of the experiment designed based on this system is to study frequency response on an electromechanical system and generate Bode plots, finally, model the system. This chapter will discuss how to set up the web-based mass-spring-damper system and how to design the experiment suitable for implementation through Internet.

5.1 System Setup

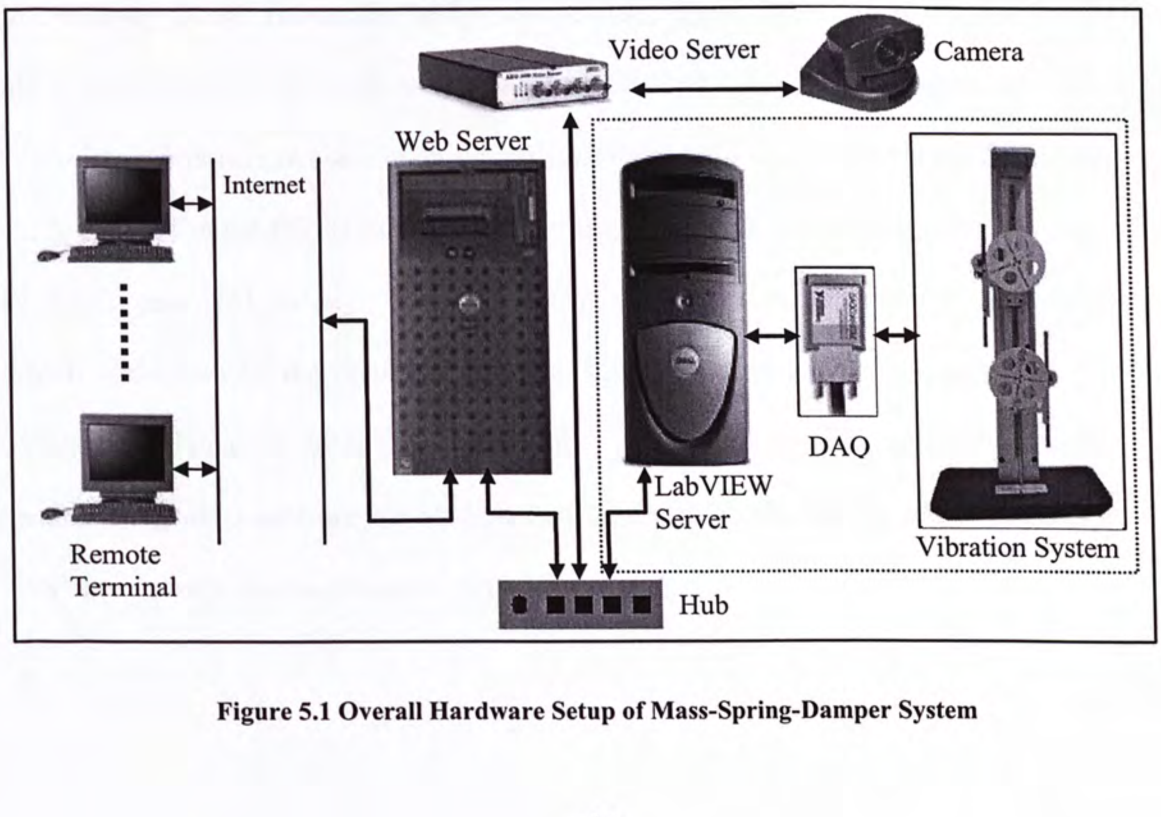

Figure 5.1 Overall Hardware Setup of Mass-Spring-Damper System

The overall hardware setup shown in Figure 5.1 has also been presented in Chapter 2. Here we will zoom in the local setup in the dashed line box in Figure 5.1, and reproduce it in Figure 5.2.

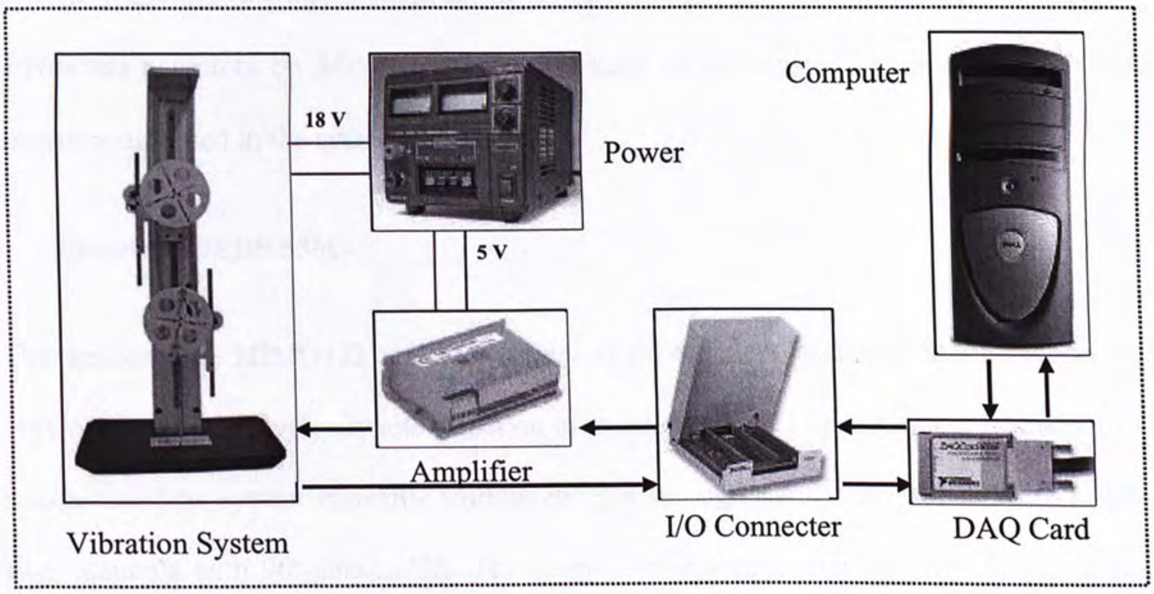

Figure 5.2 Local Setup of Mass-Spring-Damper System

In this setup, the PC runs as the bridge between the Intranet system and the plant. Facing the plant system, it is the controller server, which runs LabVIEW software. Mainly, this controller server acts in controlling the plant and measuring the states via the DAQ interface cards plugged in the PC. Those cards communicate with the plant through the I/O connector. In detail, one card, through output channel, sends the control signals to the amplifiers, which connected to the respective motors, hence to control the rotation of the motors. While the other card, through input channel, communicates with the encoder to get the feedback signal to measure the rotation state of the respective motor. Following this whole description, we will describe each part of this system.

- **Phimatic Vibration System (MIMO123)**

The MIMO123 is a training system designed to help students to learn vibration and control system. It features a coupled mass-spring-damper system. A 4-channel DC servo amplifier drives the actuators on MIMO123. The positions of the masses are made available by encoders mounted in the system.

- **Encoder (HEDS 5500)**

The encoders in MIMO123 are incremental shaft encoders designed for indication and control of both shaft velocity and direction of rotation as well as positioning. Inside, a LED source and lens system transmits collimated light through a low inertia metal disc to give two channels with 90°-phase shift. The single 5-volt supply and the two-channel digital output signals are interfaced with a 5-pin connector. The two channels are called ChA and ChB, and Figure 5.3 shows the Output signal with clockwise rotation. Indeed, the direction of rotation is determined by the phase lead or lag between ChA and ChB.

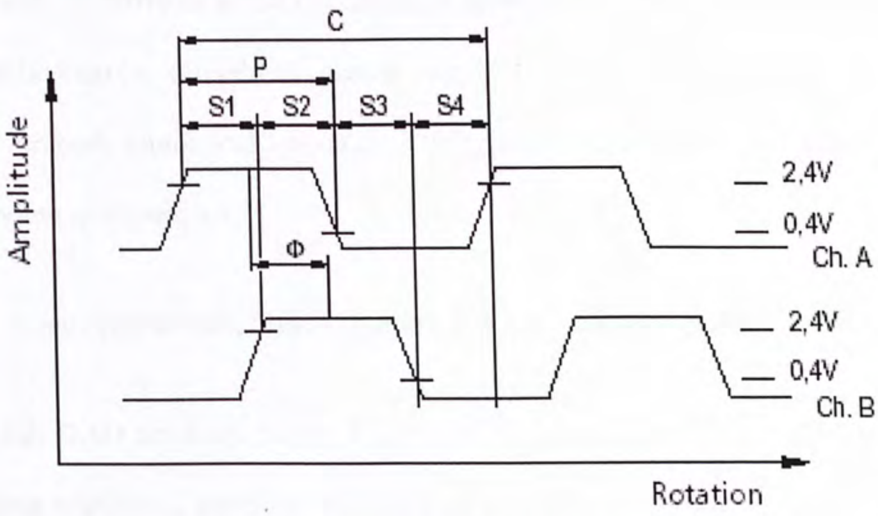

Figure 5.3 Output Signals of the Encoder

- **DC Brush Servo Amplifier (Model 403)**

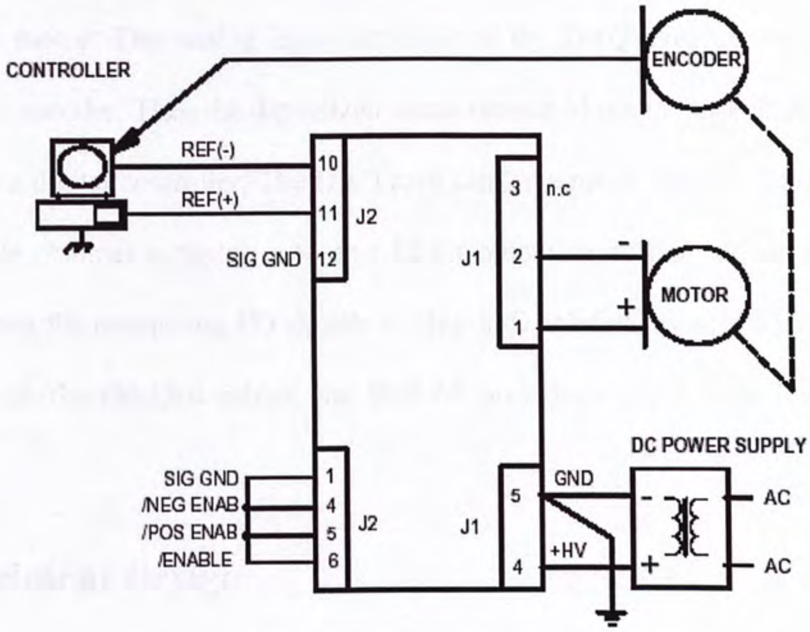

Figure 5.4 Typical Connection of the Amplifier

Since the control signal can not drive the motors directly, an amplifier is necessary. Model 403 is a complete PWM servo amplifier for application using DC Brush motors in torque (current) mode. It provides a full complement of features for motor control. These include remote inhibit/enable, directional enable inputs for connection to limit switches, and protection for both motor and amplifier. The typical connection of the amplifier and the motor is shown in Figure 5.4.

- **DAQ Cards (NI 6036E, NI6703) and I/O Connector (SCB-68)**

In Figure 5.2, DAQ cards are plugged in the PC. In general, data acquisition is the process of converting a physical quantity (such as temperature or pressure) into an electrical signal and measuring the signal in order to extract useful information. The DAQ card can act as a

D/A (Digital to Analogue) and A/D (Analogue to Digital) converter. In our setup, the output channel, which is connected to the ref. of the amplifier, sends the amplified control signal to the motor. The analog input channels of the DAQ card are connected to the outputs of the encoder. Then the digitalized measurement of the motor will be acquired and processed by a digital controller. The DAQ card can have up to 500 kS/s (kilo Samples per second) single channel scanning rate and 12-bit output resolution. Also, a shielded I/O connector block for interfacing I/O signals to plug-in DAQ devices with 68-pin connectors. Combined with the shielded cables, the SCB-68 provides rugged, very low-noise signal termination.

5.2 Experiment Design

The objective of this experiment is to study frequency response on an electromechanical system and generate Bode plots, then to model the system. Before the experiment, we will first derive the formulas of concerned transfer functions from the mathematical model with unknown parameters. Thus by conducting the designed web-based experiment, we will finally obtain the exact transfer functions.

5.2.1 System Modeling

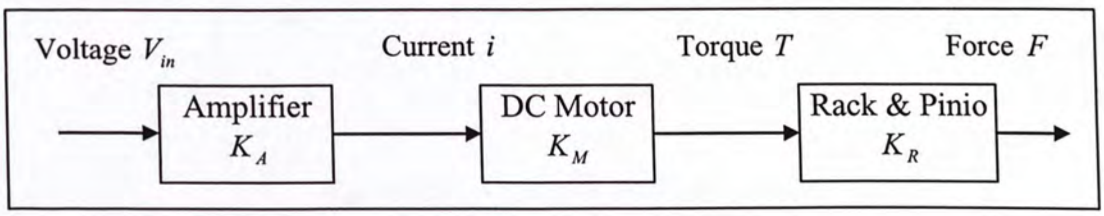

Figure 5.55 Block Diagram for Electromechanical Portion of the System

The block diagram of the open loop system is shown in Figure 5.5. The power amplifier-DC motor used in the system generates a torque, T which is proportional to the input voltage V_{in}. The torque is transformed to a linear force F, by a rack and pinion device. As a result, we obtain

$$\text{Current } i = V_{in} \times K_A,$$

$$\text{Torque } T = i \times K_M,$$

$$\text{Force } F = T \times K_R = V_{in} \times K_A \times K_M \times K_R. \quad (5.1).$$

On the other hand, Figure 5.6 shows the schematic structure of the system.

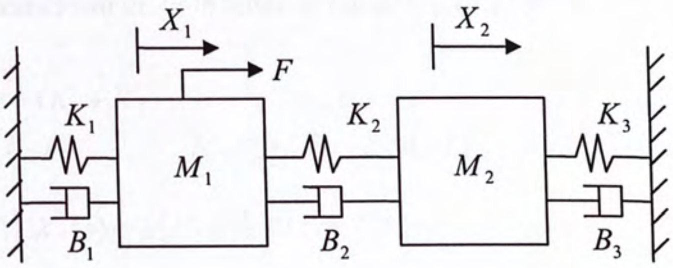

Figure 5.6 Schematic Structure of Mass-Spring-Damper System

From Figure 5.6, we can find the free body diagram,

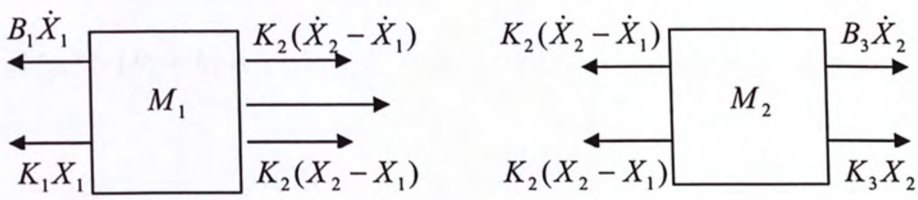

Figure 5.7 Free Body Diagrams of M1 and M2

where the parameters are listed in Table 5.1.

M_1	Equivalent Mass 1	X_1	Displacement of M_1
M_2	Equivalent Mass 2	X_2	Displacement of M_2
B_1	Viscous Damping Coefficient 1	K_1	Spring Constant 1
B_2	Viscous Damping Coefficient 2	K_2	Spring Constant 2
B_3	Viscous Damping Coefficient 3	K_3	Spring Constant 3
F	Force applied to M_1		

Table 5.1 Mass-Spring-Damper System Parameters

From the free body diagram above, two differential equations can be achieved as follows,

$$M_1\ddot{X}_1 + B_1\dot{X}_1 + B_2(\dot{X}_1 - \dot{X}_2) + K_1X_1 + K_2(X_1 - X_2) = F$$
$$M_2\ddot{X}_2 - B_2\dot{X}_2 + B_2(\dot{X}_2 - \dot{X}_1) - K_3X_2 + K_2(X_2 - X_1) = 0 \qquad (5.2)$$

Performing Laplace transform on both sides of equations (5.2) gives

$$\begin{bmatrix} M_1s^2 + (B_1 + B_2)s + (K_1 + K_2) & -(B_2s + K_2) \\ -(B_2s + K_2) & M_2s^2 + (B_2 - B_3)s + (K_2 - K_3) \end{bmatrix} \begin{bmatrix} X_1(s) \\ X_2(s) \end{bmatrix} = \begin{bmatrix} F(s) \\ 0 \end{bmatrix} \qquad (5.3)$$

with $X_1(s) = L\{X_1(t)\}, X_2(s) = L\{X_2(t)\}, F(s) = L\{F(t)\}$.

Solving (5.3) gives

$$X_1(s) = \frac{(B_2s + K_2)X_2(s) + F(s)}{M_1s^2 + (B_1 + B_2)s + (K_1 + K_2)} = \frac{(B_2s + K_2)X_2(s) + F(s)}{P(s)}$$
$$X_2(s) = \frac{(B_2s + K_2)X_1(s)}{M_2s^2 + (B_2 - B_3)s + (K_2 - K_3)} = \frac{(B_2s + K_2)X_1(s)}{Q(s)} \qquad (5.4)$$

with $P(s) = M_1s^2 + (B_1 + B_2)s + (K_1 + K_2), Q(s) = M_2s^2 + (B_2 - B_3)s + (K_2 - K_3)$. Hence,

$$X_1(s) = \frac{F(s)Q(s)}{P(s)Q(s) - (B_2s + K_2)^2},$$

$$X_2(s) = \frac{F(s)(B_2s + K_2)^2}{P(s)Q(s) - (B_2s + K_2)^2}.$$

Therefore, we get $X_1 / V_{in}, X_2 / V_{in}$, and X_2 / X_1 respectively, as follows,

$$\frac{X_1}{V_{in}} = \frac{K_A K_M K_R Q(s)}{P(s)Q(s) - (B_2 s + K_2)^2}$$
$$\frac{X_2}{V_{in}} = \frac{K_A K_M K_R (B_2 s + K_2)}{P(s)Q(s) - (B_2 s + K_2)^2}$$
$$\frac{X_2}{X_1} = \frac{(B_2 s + K_2)}{Q(s)}. \tag{5.5}$$

5.2.2 Experiment Procedures

Step 1: Access the experiment

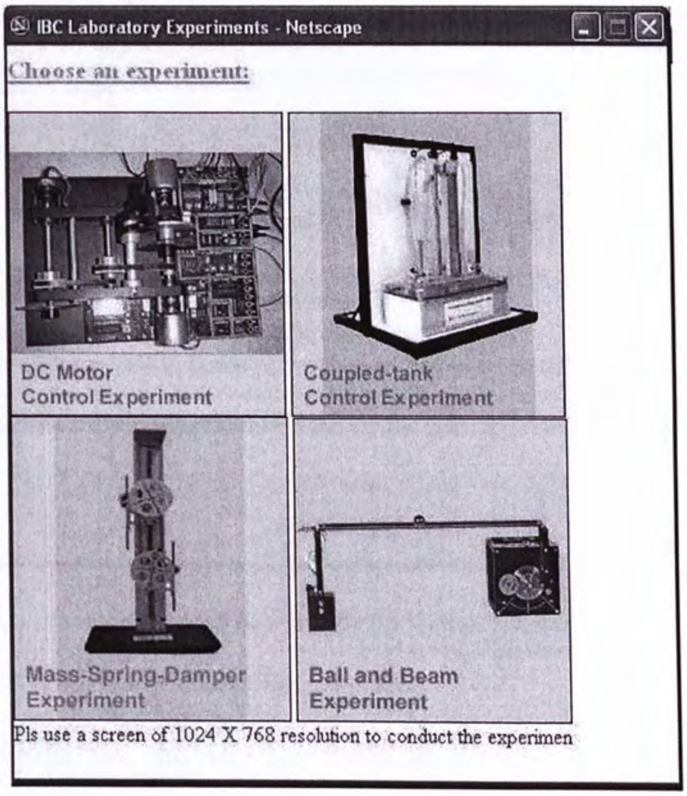

Figure 5.8 "Choose an Experiment" Window

Access the Internet-Based Control (IBC) Laboratory via http://acclserv.acae.cuhk.edu.hk. The suggested browser is Netscape 7.0 or above. By clicking the "Conduct Experiment" link, a window as Figure 5.8 appears. Then choose the mass-spring-damper experiment in the window. Next, the authority should be verified. The user should input the Login ID and

Password in the authority verification window as Figure 5.9. For each experiment, the assigned IDs or passwords are different. In the authority verification window, some important notices are distributed to the user. It should be noted that after each experiment, the results including the used parameters will be recorded in the user's personal database. However, nothing will be recorded for the user login as a "guest". After the authority is verified, the experiment interface appears which has been shown in Figure 2.7.

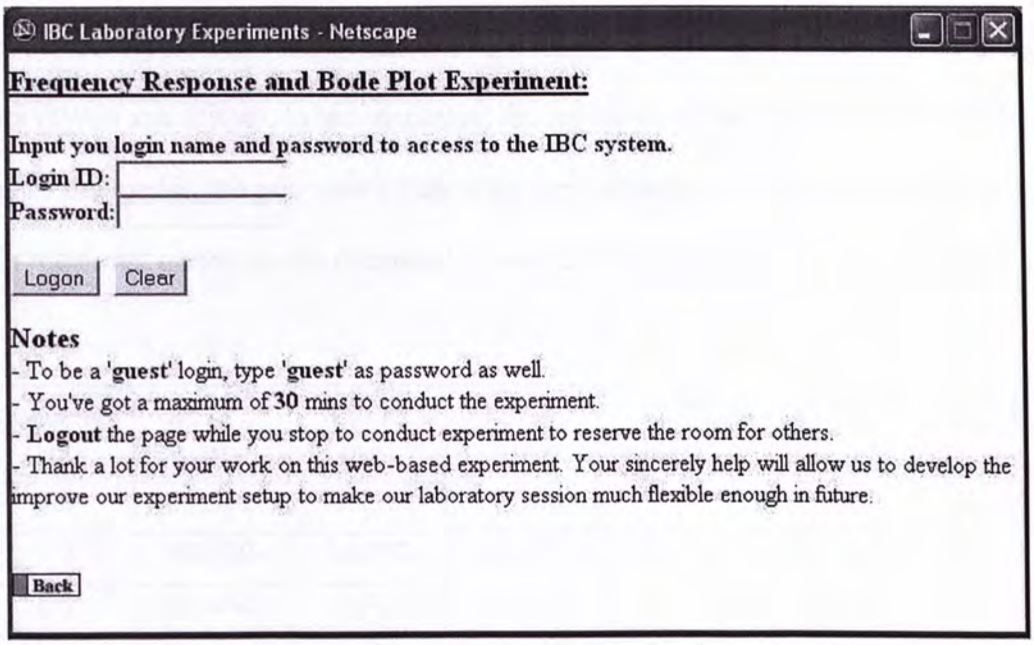

Figure 5.9 Authority Verification Window

Step 2: Conduct the experiment and collect the data

In the experiment interface, the user can input the parameters in the command window (Figure 5.10), and then apply the parameters to the remote plant, after turn on the power button.

As introduced before, the Phimatic vibration system has four DC servos and four encoders, to completely understand the properties of the system, it is necessary to check the system response by acquiring all encoders by applying different inputs on different servo motors.

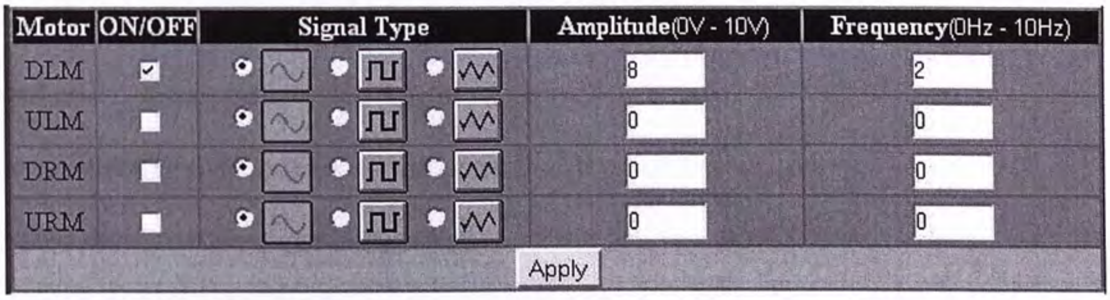

Figure 5.10 Command Window for Mass-Spring-Damper Experiment

In particular, two linear motors (DLM and ULM) drive the motion of the mass, and the rotational inertia of the masses can be adjusted by change the speed of two rotational motors (DRM and URM). In the modeling, the inputs on linear motors are regarded as the inputs of the model, the positions of the mass are the outputs of the model, and the inputs on the rotational motor (or the rotational velocities of the masses) are the parameters of the model.

Frequency (Hz)	X_1/V_{in} (dB)	X_2/V_{in} (dB)	X_2/X_1 (dB)	X_1/V_{in} (degree)	X_2/V_{in} (degree)	X_2/X_1 (degree)
0.5	17.501	9.173	-8.328	-11.835	-16.650	-5.814
1.0	18.689	11.081	-7.608	-21.672	-30.024	-8.352
1.5	18.062	13.481	-4.760	-40.740	-55.370	-14.630
2.0	14.194	11.481	-2.713	-56.016	-79.448	-23.432
2.5	14.087	10.725	-3.362	-59.265	-102.600	-43.335
3.0	9.897	5.460	-4.437	-68.244	-129.840	-61.596
3.5	8.383	-0.561	-8.943	-68.406	-132.183	-63.777
4.0	6.547	-6.021	-12.563	-88.435	-156.348	-67.913
4.5	3.522	-12.041	-15.563	-90.482	-167.324	-76.842
5.0	1.023	-15.783	-16.806	-90.912	-171.230	-80.318

Table 5.2 Frequency Responses

As an experiment example, here, we only consider a simple case, that is, study the responses of two masses when one motor drives. By Applying inputs with different amplitudes and frequencies, we observe and record the responses. And we can calculate the relations as illustrated in Table 5.2.

After collecting the experiment data, click the "log off" link to quit.

Step 3: Analyze Experiment Data

The data acquired through the web-based experiment can be analyzed off-line in MATLAB. As an example, we illustrate how to built the transfer function between X_1 and X_2 from the data in Table 5.2, by the Bode plots technique introduced in Chapter 4. The Bode plots from Table 5.2 are shown in Figures 5.11-5.13. Focus on the transfer function between X_1 and X_2, we only consider Figure 5.13.

First, we have the 2nd order relation between X_1 and X_2 as the last equation of (5.5), in the form of $\frac{X_2(s)}{X_1(s)} = \frac{K(s/w_1+1)}{(s/w_n)^2 + 2\xi s/w_n + 1}$.

From Figure 5.13, it is ready to measure $w_1 \cong 5.50$ rad/sec and $20\log K \cong -8.33$, hence $K \cong 0.383$, where w_1 is the frequency at which the two magnitude asymptotes intersect, and K is the magnitude when the frequency is sufficiently small. Then plot the Bode plots for $0.383(s/5.50+1)$ as Figure 5.14, and the data are record on Table 5.3.

Frequency(Hz)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
Magnitude(dB)	-7.14	-4.74	-2.48	-0.50	1.18	2.63	3.89	4.97	5.94	6.84
Phase(degree)	29.8	48.8	59.6	66.2	70.6	73.6	75.9	77.6	78.9	80.0

Table 5.3 Frequency Responses of $0.383(s/5.50+1)$

Then, the Bode plots of $\frac{1}{(s/w_n)^2 + 2\xi s/w_n + 1}$ can be achieved by subtracting Figure 5.13 from Figure 5.14. And the result is shown in Figure 5.15. From Figure 5.15, it can be measured that $w_n \cong 12.6$ rad/sec and $w_2 \cong 3.20$ rad/sec , where w_n is the break point frequency at which the phase is -90°, and w_2 is the frequency at which the phase asymptote intersects the 0° line. This corresponds to $w_n / w_2 \cong 3.94$, which in turn corresponds to $\xi \cong 0.8$, as seen on the normalized response curves of second order system.

Now, the final model of transfer function is given by $\dfrac{X_2(s)}{X_1(s)} = \dfrac{0.383(s/5.50+1)}{(s/12.6)^2 + 1.60s/12.6 + 1}$.

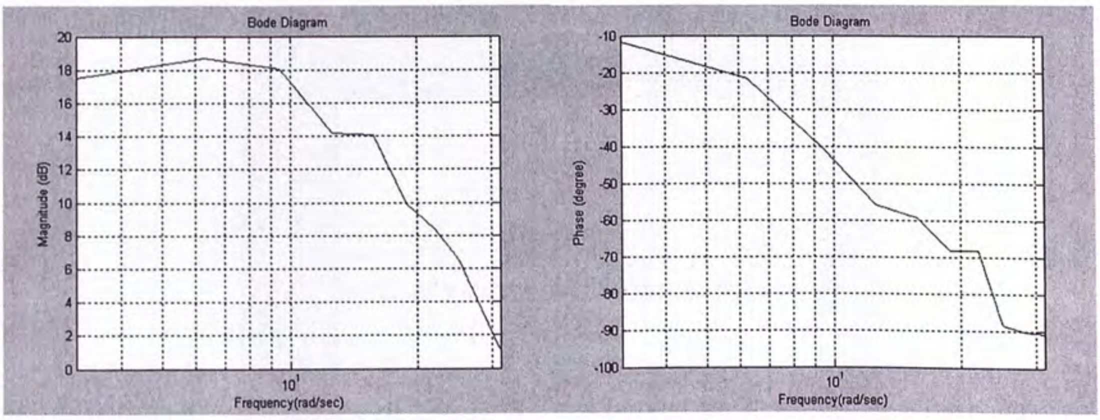

Figure 5.11 Magnitude and Phase Plots of X_1 / V_{in}

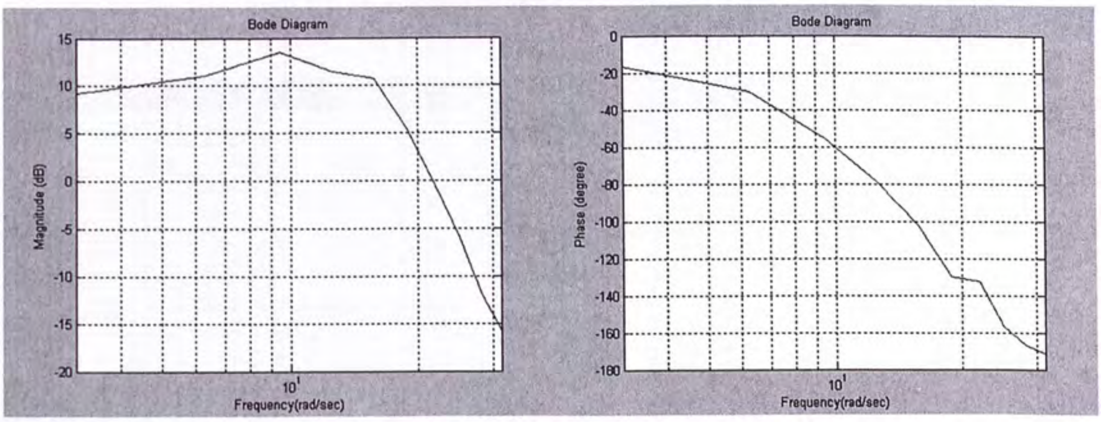

Figure 5.12 Magnitude and Phase Plots of X_2 / V_{in}

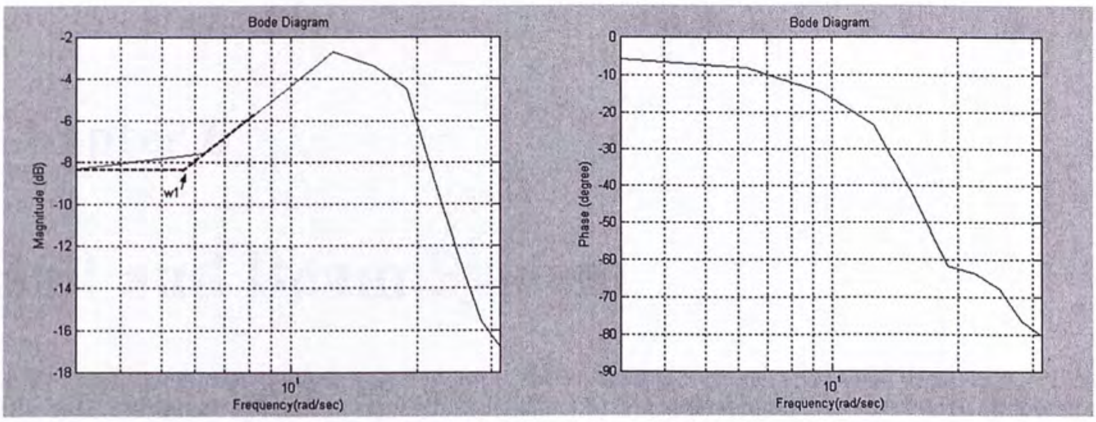

Figure 5.13 Magnitude and Phase Plots of X_2 / X_1

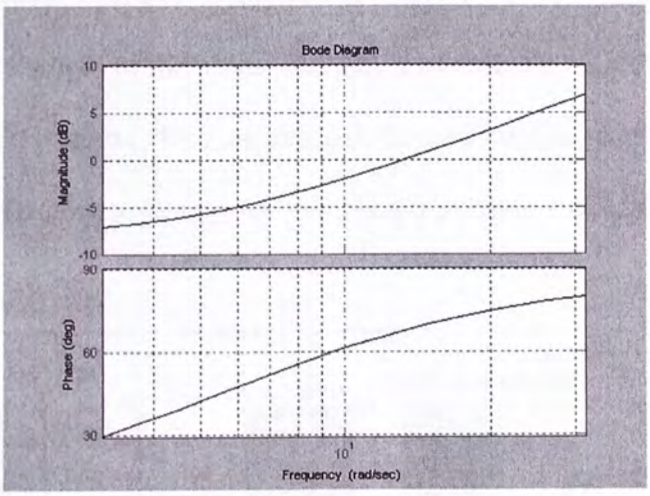

Figure 5.14 Magnitude and Phase Plots of $0.383(s/5.50+1)$

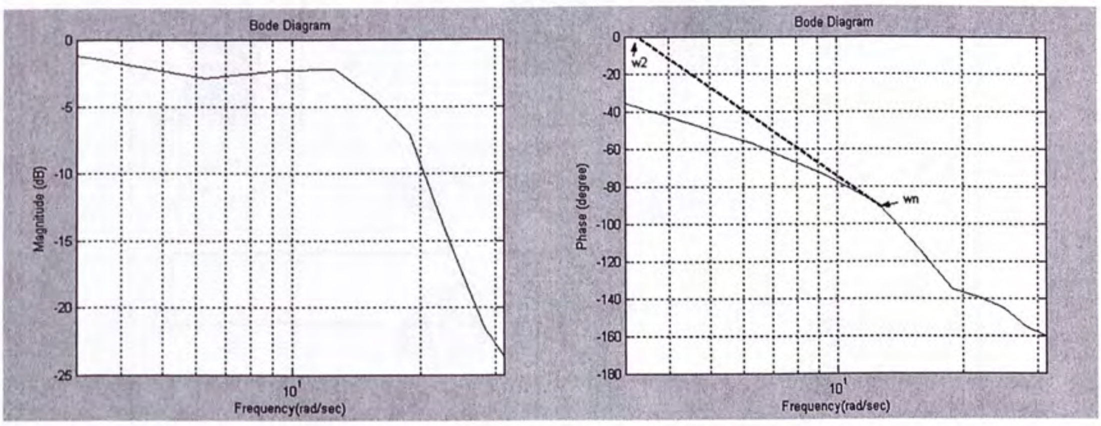

Figure 5.15 Magnitude and Phase Plots of $1/\left[(s/w_n)^2 + 2\xi s/w_n + 1\right]$

Chapter 6

Ball and Beam System

This ball and beam system is newly established in the web-based laboratory. In this system, DC motor drives a beam such that the motor angle controls the tilt angle of the beam, and a ball travels along the length of the beam. The aim is to design a control system to track the ball to a commanded position. This chapter will discuss how to setup the web-based ball and beam system and how to design the experiment suitable for implementation through Internet.

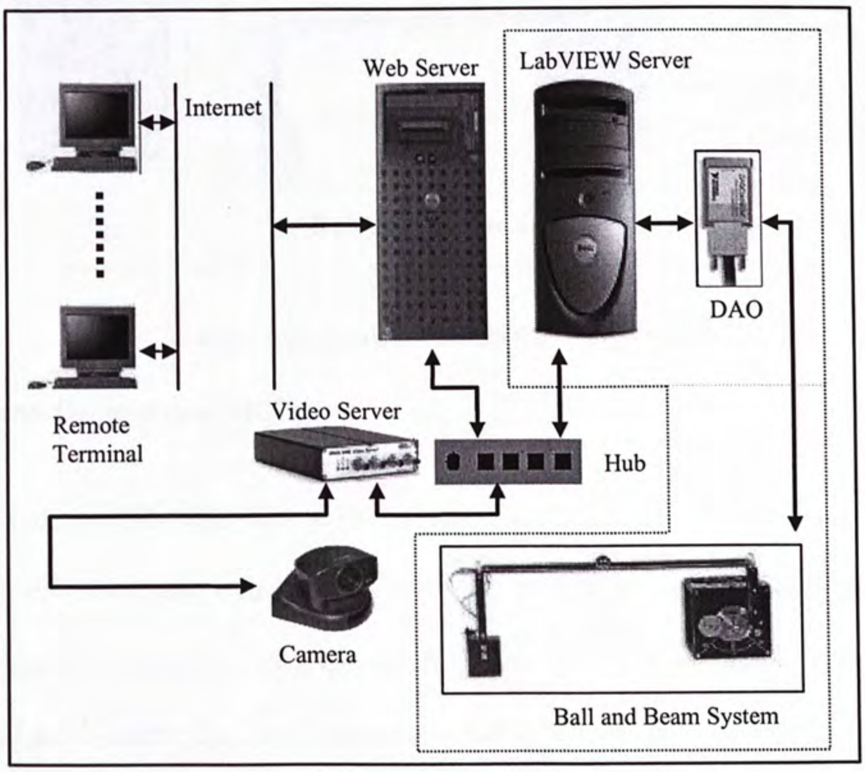

Figure 6.1 Overall Hardware Setup of Ball and Beam System

6.1 System Setup

Figure 6.1 shows the overall hardware architecture of the ball and beam system. From this figure, it is seen that the system also has the same basic architecture as what has been described in Chapter 3. The particular character of this system is the on site plant, that is, the part in the dashed line box. This part is demonstrated in more detail in Figure 6.2. Next, each component in Figure 6.2 will be described one by one.

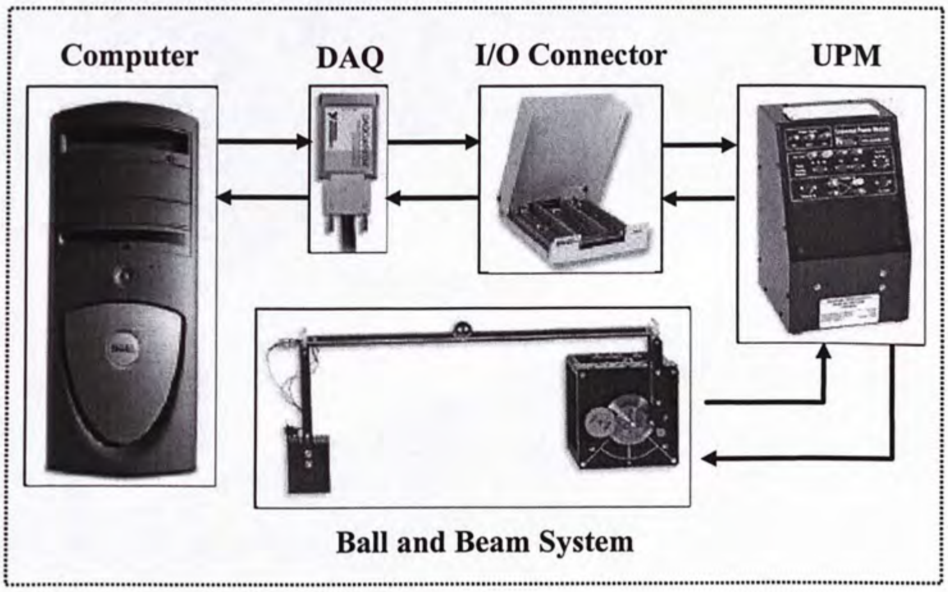

Figure 6.2 Local Setup of Ball and Beam System

- **Ball and Beam Apparatus**

Figure 6.3 depicts the ball and beam module coupled to the SRV02 plant in the correct configuration. The beam consists of a steel rod in parallel with a nickel-chromium wire-wound resistor forming the track on which the metal ball is free to roll. The SRV02 plant consists of a DC motor in a solid aluminum frame. The motor is equipped with a gearbox. The gearbox output drives external gears. The basic unit is equipped with a potentiometer to measure the output/load angular position. The motor drives a lever arm which is coupled to a track upon which a rolling ball rests. The position of the ball is obtained by measuring the voltage at the steel rod. When the ball rolls along the track, it acts as a wiper similar to a potentiometer resulting in the position of the ball.

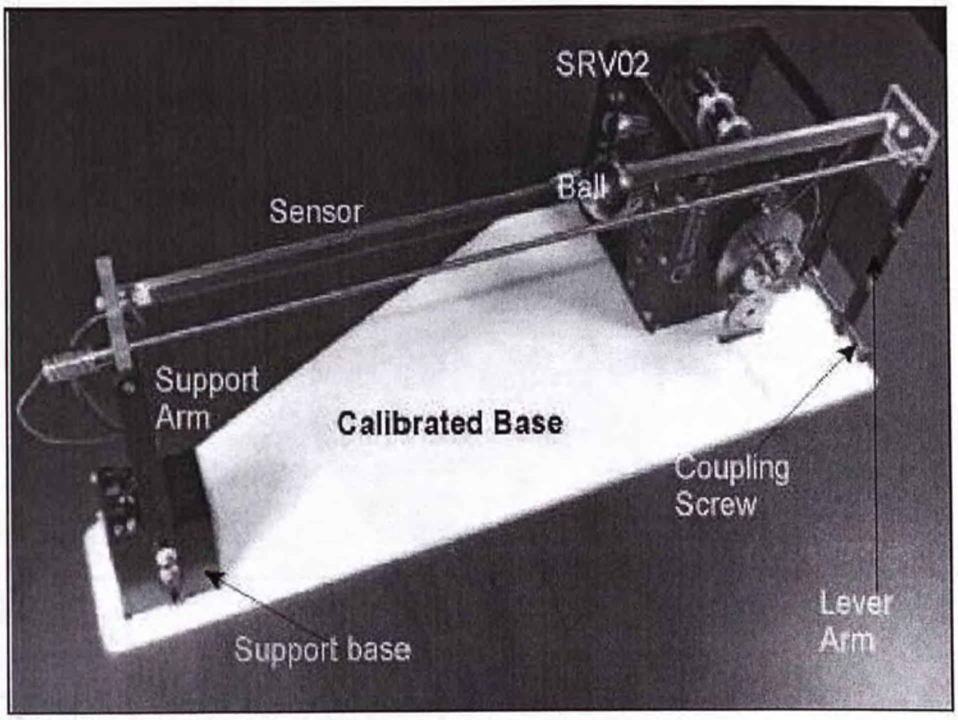

Figure 6.3 Description of Ball and Beam Apparatus

- **Universal Power Modules (UPM)**

The Universal Power Module (UPM-15-03) is used as an amplifier to drive the motor and it also provides convenient channels from the controller to the plant. The UPM features below.

(a) [1] ± 12 Volt Power Supply

(b) [4] Analog Sensor Inputs

(c) [1] Power Amplified Analog Output (the gain is set by the choice of cable).

The above mentioned ports all provide test points alongside the standard connections to provide complete access to the inherent signals. These test points can be monitored externally if the user wishes (i.e. through an oscilloscope).

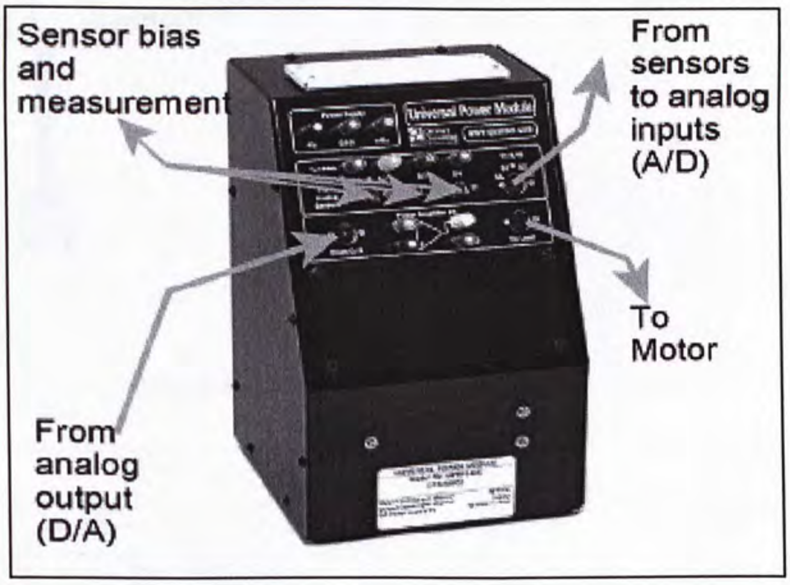

Figure 6.4 Universal Power Module

- **DAQ Cards (NI 6036E, NI6703) and I/O Connector (SCB-68)**

Same as those introduced in the mass-spring-damper system in Chapter 5.

6.2 Experiment Design

Three control experiments have been designed with the ball and beam system as a platform, those are, PD controller, feedfoward controller, and internal model controller. Before implementing these controllers, it is necessary to understand the plant properties. To this end, the system model will be studied.

6.2.1 System Modeling

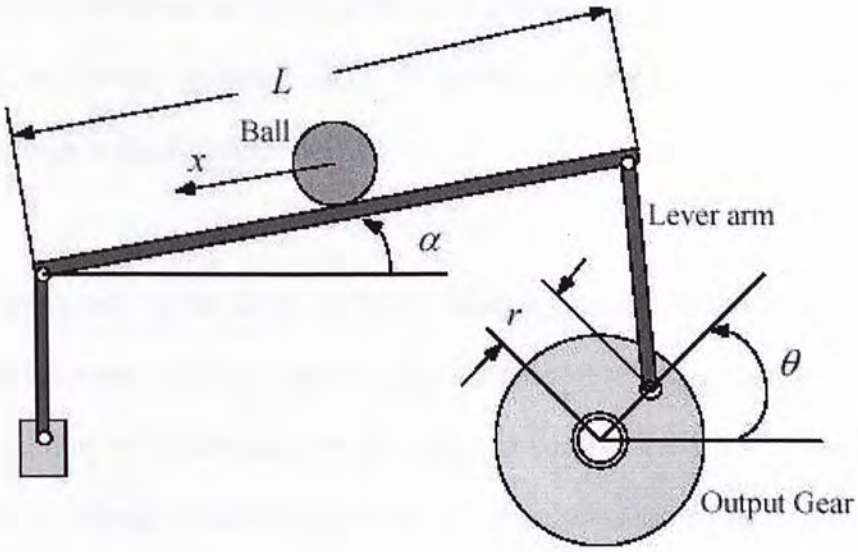

Figure 6.5 Ball and Beam Mathematical Illustration

Symbol	Description	Symbol	Description
L	Beam Length (*L=16.75 in*)	r	Lever arm offset (*r=1 in*)
X	Ball Position	m	Mass of the ball
α	Beam pitch	R	Radius of the ball
θ	Servo load gear angle (radians)	J	Ball's moment of inertia
F_{tx}	Translational force on the ball	F_{rx}	Rotational force on the ball
g	Earth's gravitational constant	V_{in}	Motor voltage
i_m	Armature current	R_m	Armature resistance
L_m	Armature inductance	θ_m	Armature angular position
K_t	Motor torque constant	K_g	Gear ratio
K_m	Back EMF constant	J_l	Load inertia
J_m	Motor Inertia	τ_m	Motor shaft torque

Table 6.1 Ball and Beam System Paramters

Figure 6.5 illustrates the mathematical model of the ball and beam system, and Table 6.1 is a list of the nomenclature used in Figure 6.5 and the other illustration and derivations in this chapter. Figure 6.5 shows the simplified model of ball and beam. By examining the forces acting on the ball, we have the translational force due to gravity, and we have a rotational force due to the torque produced by the rotational acceleration of the ball. First, the gravitational force in the x-direction is

$$F_{tx} = mg\sin\alpha. \tag{6.1}$$

The torque produced by the ball's rotational motion is equal to the radius of the ball multiplied by the rotational force (opposing the direction of travel). Using Newton's second equation of motion, we also know that the torque is equal to the ball's moment of inertia multiplied by its angular acceleration, which then can be written as its moment of inertia multiplied by the double-derivative of its translational motion (x) divided by its radius yielding the following expression,

$$T_r = F_{rx}R = Ja = J\frac{\ddot{x}}{R}. \tag{6.2}$$

We now take the ball's moment of inertia $J = \frac{2}{5}mR^2$ and rearrange equation (6.2) to solve the rotational force,

$$F_{rx} = \frac{2}{5}m\ddot{x}. \tag{6.3}$$

Given all the forces acting on the rolling ball, we can again apply Newton's second law of motion and equate the ball's mass multiplied by its acceleration to the sum of forces acting on the ball,

$$m\ddot{x} = \Sigma F = F_{tx} - F_{rx} = mg\sin\alpha - \frac{2}{5}m\ddot{x}. \tag{6.4}$$

Finally, we will rearrange equation (6.4) yielding

$$\ddot{x} = \frac{5}{7} g \sin\alpha. \tag{6.5}$$

To linearize the above equation, note that $\sin\alpha = \alpha$ for small α (in radians). Since the pitch of the beam will always remain relatively small, this estimation will hold true for this particular experiment yielding a final, linearized transfer function of

$$\frac{X(s)}{\alpha(s)} = \frac{5g}{7s^2}. \tag{6.6}$$

Referring back to the illustration of Figure 6.5, let us refer to the arc length traveled by the level arm as *Arc*. If we measure both angles in radians, we get the following expression,

$$\theta\, r = Arc = \alpha L \rightarrow \theta = \frac{L}{r}\alpha. \tag{6.7}$$

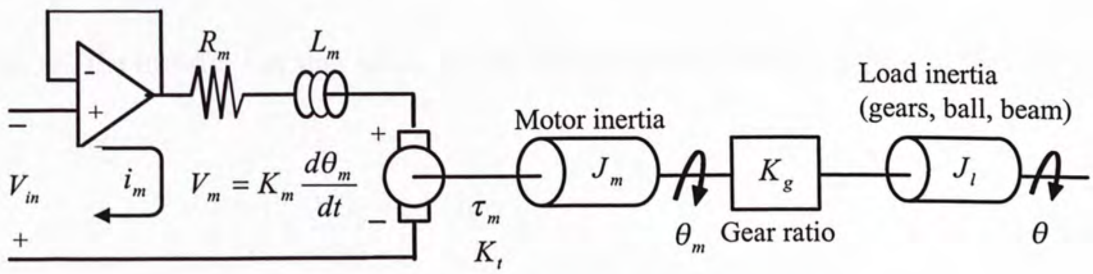

Figure 6.6 Electro-mechanical Servomotor Model

To complete the system derivations, we need to know the transfer function from motor voltage V_{in} to output angle θ. To this end, we will refer to Figure 6.6. The electrical dynamics can be described by

$$V_{in} = R_m i_m + L_m \frac{di_m}{dt} + K_m \frac{d\theta_m}{dt}$$

and the mechanical equation of motion can be described by

$$\tau_m = \left(J_m + \frac{J_l}{K_g^2} \right) \frac{d^2\theta_m}{dt^2}.$$

Because this is an armature controlled configuration, the field current in the motor is held constant and the motor torque is proportional to the armature current, i.e.,

$$\tau_m = K_t i_m.$$

Using the gear ratio $\theta_m = K_g \theta$, we have the transfer function from V_{in} to θ as follows, neglecting the armature inductance L_m,

$$\frac{\theta(s)}{V_{in}(s)} = \frac{1}{s\left(s\dfrac{R_m J_{eq}}{K_t K_g} + K_m K_g \right)}, \tag{6.8}$$

where $J_{eq} = K_g^2 J_m + J_l$ is the equivalent inertia seen at the output of the gearbox. Overall, the transfer function of the system between motor input and the ball position is

$$\frac{X(s)}{V_{in}(s)} = \frac{X(s)}{\alpha(s)} \frac{\alpha(s)}{\theta(s)} \frac{\theta(s)}{V_{in}(s)} = \frac{5gr}{7Ls^3\left(s\dfrac{R_m J_{eq}}{K_t K_g} + K_m K_g \right)}. \tag{6.9}$$

6.2.2 PD Controller Design

From equation (6.9), it is known that the ball and beam model is 4th order. Therefore, designing a controller to meet time specifications becomes increasing complicated. The objective of this experiment is to design a controller by implement two independent control loops.

(i) Inner loop: to control the position of the servo gear to a command angle.

(ii) Outer loop: to control the position of the ball on the beam by manipulating the servo angle.

The goal is to design the inner loop to be sufficiently faster than the outside loop to ensure that the servo plant dynamics do not interfere with the ball controller dynamics. The following table lists the recommended time specifications to be designed for each loop.

	Time to Peak (T_p)	Damping Ratio (ξ)	Natural Frequency (ω_n)	Percent Overshoot (%OS)
Inner Loop	*0.200 s*	*0.707*	*22.2 rd/s*	*4.6 %*
Outer Loop	*1.5 s*	*0.707*	*2.96 rd/s*	*4.6 %*

Table 6.2 Controller Time Specifications

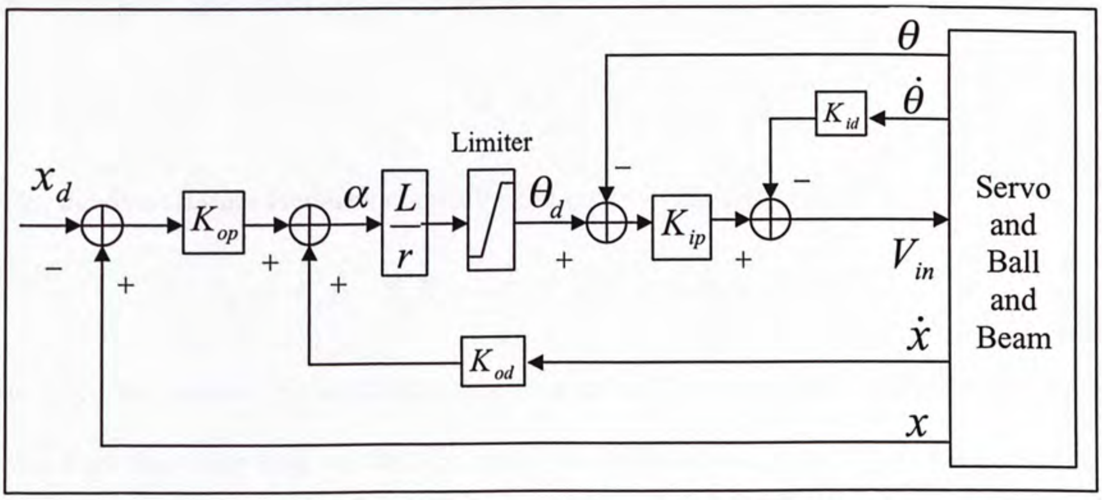

Figure 6.7 PD Controller Block Diagram for Ball and Beam

To meet the specifications above, two separate PD (Proportional-Derivative) controllers are used for the inner and outer loops (refer to Figure 6.7). The details are given below.

We have known that the inner loop controls the servo angle to a desired set point angle, while the outer loop controls the ball position by commanding a set point position. By design, the inner loop ensures that the servo angle θ tracks a desired angle θ_d, that is, the motor input is chosen by

$$V_{in} = K_{ip}(\theta_d - \theta) - K_{id}\dot{\theta} \tag{6.10}$$

where K_{ip} (V/rad) is the inner loop proportional gain, and K_{id} (Vs/rad) is the inner loop derivative gain. Similarly, the outer loop controls the ball position using the PD feedback law as follows,

$$\alpha = K_{op}(x - x_d) - K_{od}\dot{x} \tag{6.11}$$

where K_{op} (rad/cm) is the outer loop proportional gain, and K_{od} (rad s/cm) is the outer loop derivative gain. Physically, θ_d is computed from α as,

$$\theta_d = \frac{L}{r}\alpha. \tag{6.12}$$

Now, the overall state feedback controller can be implemented of the form,

$$V_{in} = -K_{ip}\theta - K_{id}\dot{\theta} + \frac{L}{r}K_{ip}K_{op}(x - x_d) - \frac{L}{r}K_{ip}K_{od}\dot{x}. \tag{6.13}$$

The important aspect of this design approach is that the inner loop must be considerably faster than the outer loop so that the servo plant dynamics do not affect the closed loop response of the ball controller dynamics. To meet the specifications listed in Table 6.2, and according to the parameters given in the datasheet of ball and beam module, we design the gains as follows,

K_{ip} = 7 V/rad, K_{id} = 0.75 Vs/rad, K_{op} = 0.007 rad/cm, K_{od} =0.007 rad s/cm.

There is a limiter in Figure 6.7 for the following reason. Due to the mechanical structure of the system, the "linear" relationship between α and θ only holds when $-90^0 < \theta < 90^0$

(approximately). When θ is out of this region, the relationship is actually the reverse, i.e. as θ increases, α decreases! Therefore, we need to ensure that θ does not cross the "linear" region. This cannot be ensured with a state feedback controller since the input to the system is voltage only. We can ensure that θ does not cross the region by limiting the command θ and be ensuring that the inner loop is stable all by itself.

6.2.3 Feedforward Controller Design

The linearized system equation (6.6) can also be represented in state space form. This can be done by selecting the ball's position (x) and velocity ($\dot{x}$) as the state variables and the gear angle (θ) as the input, with (6.7) in mind. The state-space representation is shown below,

$$\begin{bmatrix} \dot{x} \\ \ddot{x} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \end{bmatrix} + \begin{bmatrix} 0 \\ \dfrac{5gr}{7L} \end{bmatrix} \theta. \tag{6.14}$$

However, instead of controlling the position of ball through the gear angle θ, we will control $\ddot{\theta}$, which is essentially controlling the torque of the beam. Below is the representation of this system from (6.8),

$$\begin{bmatrix} \dot{x} \\ \ddot{x} \\ \dot{\theta} \\ \ddot{\theta} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & \dfrac{5gr}{7L} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -\dfrac{K_t K_m K_g^2}{R_m J_{eq}} \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \\ \theta \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \dfrac{K_t K_g}{R_m J_{eq}} \end{bmatrix} V_{in}. \tag{6.15}$$

Let $x_1 = x, x_2 = \dot{x}, x_3 = \theta, x_4 = \dot{\theta}, u = V_{in}, y = x$, and

$$X=\begin{bmatrix}x_1\\x_2\\x_3\\x_4\end{bmatrix},F=\begin{bmatrix}0&1&0&0\\0&0&\frac{5gr}{7L}&0\\0&0&0&1\\0&0&0&-\frac{K_tK_mK_g^2}{R_mJ_{eq}}\end{bmatrix},G=\begin{bmatrix}0\\0\\0\\\frac{K_tK_g}{R_mJ_{eq}}\end{bmatrix},H=\begin{bmatrix}1&0&0&0\end{bmatrix},$$

we rewrite (6.15) in compact form $\dot{X}=FX+Gu,\ y=HX$.

Next, we will design a controller for this physical system that utilizes full state feedback control. Recall, that the characteristic polynomial for this closed-loop system is the determinant of $(sI-(F-GK))$. The pair (F,G) is controllable, which can be verified by calculating

$$F=\begin{bmatrix}0&1&0&0\\0&0&41.79\ \text{cm/s}^2&0\\0&0&0&1\\0&0&0&-0.2828(\text{V}^2\ \text{s}^2)/(\text{rad}\ \Omega\ \text{kg}\ \text{cm}^2)\end{bmatrix},$$

$$G=\begin{bmatrix}0\\0\\0\\7.375\ (\text{Vs})/(\text{rad}\ \Omega\ \text{kg}\ \text{cm}^2)\end{bmatrix},$$

therefore, there exists a feedforward controller $u=-KX+Mx_d$, where K is chosen such that $(F-GK)$ is stable, and M is calculated by the way introduced in Chapter 4. In particular, $\begin{bmatrix}N_x\\N_u\end{bmatrix}=\begin{bmatrix}F&G\\H&0\end{bmatrix}^{-1}\begin{bmatrix}0_{4\times1}\\1\end{bmatrix}=\begin{bmatrix}1&0&0&0&0\end{bmatrix}^T$, that is, $N_x=\begin{bmatrix}1&0&0&0\end{bmatrix}$, and $N_u=0$. Then, $M=N_u+KN_x=K\begin{bmatrix}1&0&0&0\end{bmatrix}^T$, hence,

$$u=-KX+Mx_d=-K\left(X-\begin{bmatrix}1&0&0&0\end{bmatrix}^T x_d\right)$$

As a result, the final feedforward controller can be written the following form,

$$V_{in} = -K_1(x - x_d) - K_2\dot{x} - K_3\theta - K_4\dot{\theta}, \tag{6.16}$$

where $K = [K_1 \quad K_2 \quad K_3 \quad K_4]$.

It should be noted that the feedforward controller (6.16) has the same form as the PD controller (6.13) with $K_1 = -\frac{L}{r}K_{op}K_{ip}, K_2 = \frac{L}{r}K_{od}K_{ip}, K_3 = K_{ip}, K_4 = K_{id}$. And a schematic of this type of controller is shown as Figure 6.8, where the utilization of limiter is motivated from the PD controller.

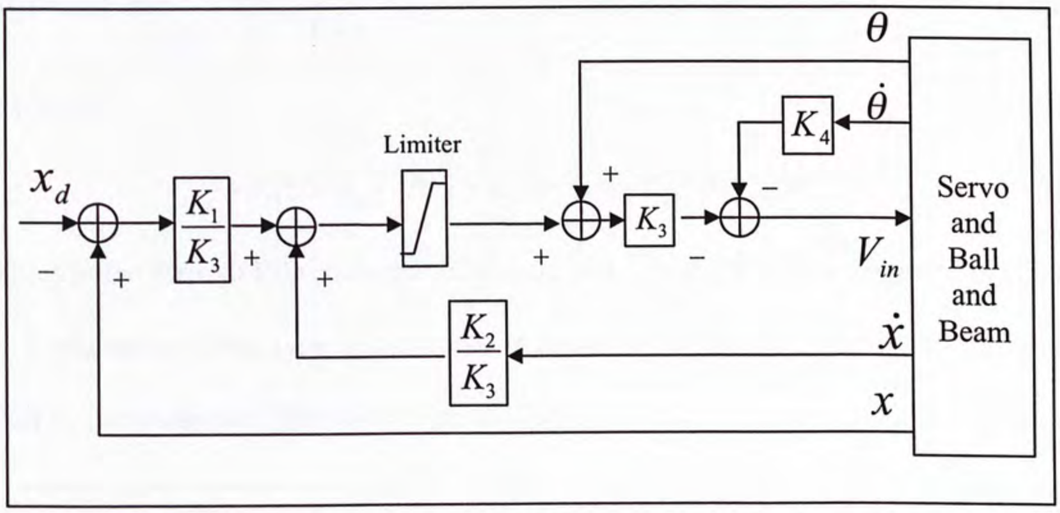

Figure 6.8 Feedforward Controller Block Diagram for Ball and Beam

6.2.4 Internal Model Controller Design

As we have introduced in Chapter 4, there is another state space controller design method besides the feedforward method in dealing with the tracking problem, that is, the internal model method. Consider the state space model derived above, form an augmented plant $\begin{cases} \dot{X} = FX + Gu \\ \dot{z} = HX - x_d \end{cases}$. Letting $X_a = \begin{bmatrix} X \\ z \end{bmatrix}$ gives

$$\dot{X}_a = \begin{bmatrix} F & 0 \\ H & 0 \end{bmatrix} \begin{bmatrix} X \\ z \end{bmatrix} + \begin{bmatrix} G \\ 0 \end{bmatrix} u + \begin{bmatrix} 0 \\ -1 \end{bmatrix} x_d = F_a x_a + G_a u + G_r x_d .$$

Then, the internal model has the form of $\begin{cases} u = K_a x_a = -K_x X - K_z z \\ \dot{z} = e \end{cases}$, where $K_a = [K_a \quad K_z]$ is such that $(F_a - G_a K_a)$ is stable. It can be verified that $(F_a,\ G_a)$ is controllable.

Denote $\bar{z} = z + \frac{K_1}{K_z} x_d$, and let $K_x = [K_1 \quad K_2 \quad K_3 \quad K_4]$, then the internal model is transformed into $\begin{cases} u = -K_x X - K_z \bar{z} + K_1 x_d \\ \dot{\bar{z}} = e \end{cases}$. It is obviously that the internal model can be rewritten as

$$V_{in} = -K_1(x - x_d) - K_2\dot{x} - K_3\theta - K_4\dot{\theta} - K_z\int(x - x_d)dt, \tag{6.17}$$

which is in the form of PID controller. Compare (6.17) with (6.13), an integer term is added. And a schematic of this type of controller is shown as Figure 6.9, where the utilization of limiter is also motivated from the PD controller.

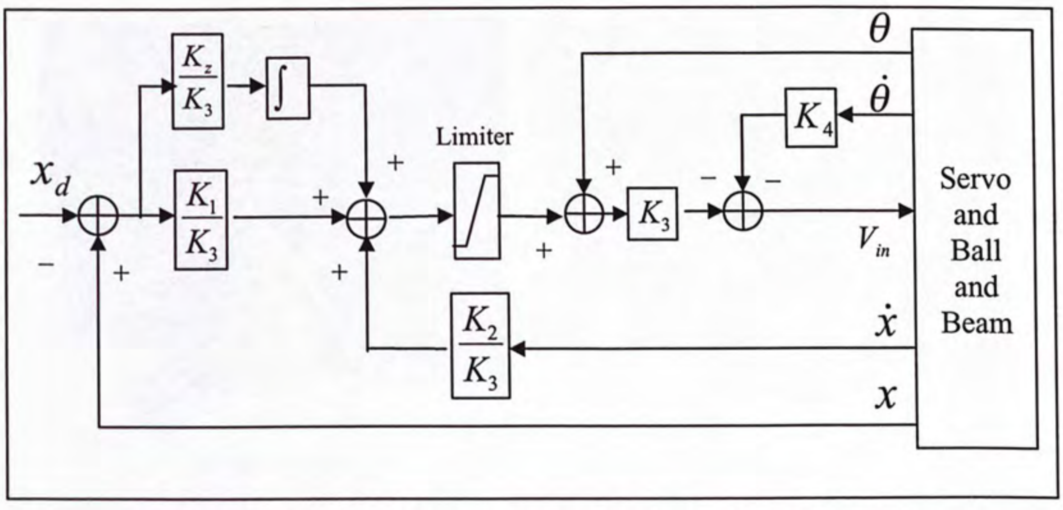

Figure 6.9 Internal Model Controller Block Diagram for Ball and Beam

6.2.5 Experiment Procedures

Step 1: Access the experiment

Follow the same instruction given for the mass-spring-damper experiment in Chapter 5, and the experiment interface appears which has been shown in Figure 2.9. Users can choose the controller type and parameters in the command window shown in Figure 6.10. After the power button is on, the command can be applied into the remote plant.

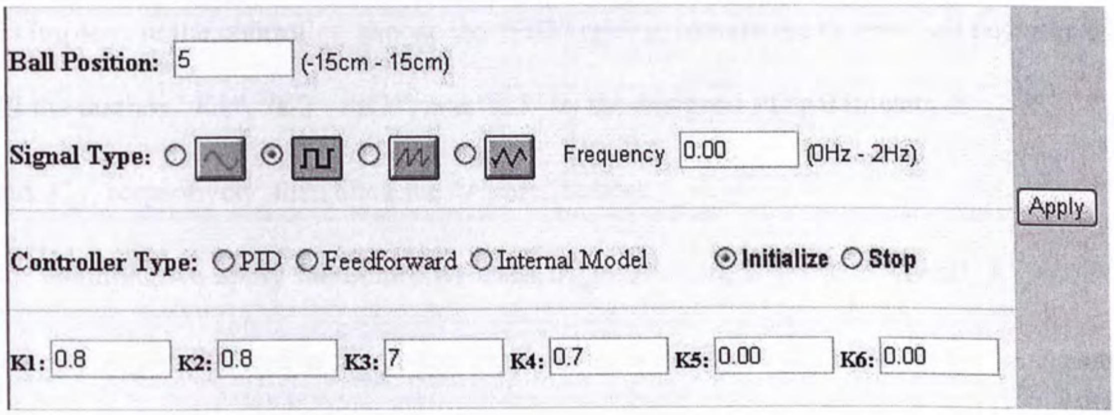

Figure 6.10 Command Window for Ball and Beam Experiment

Step 2: Initialize the motor position

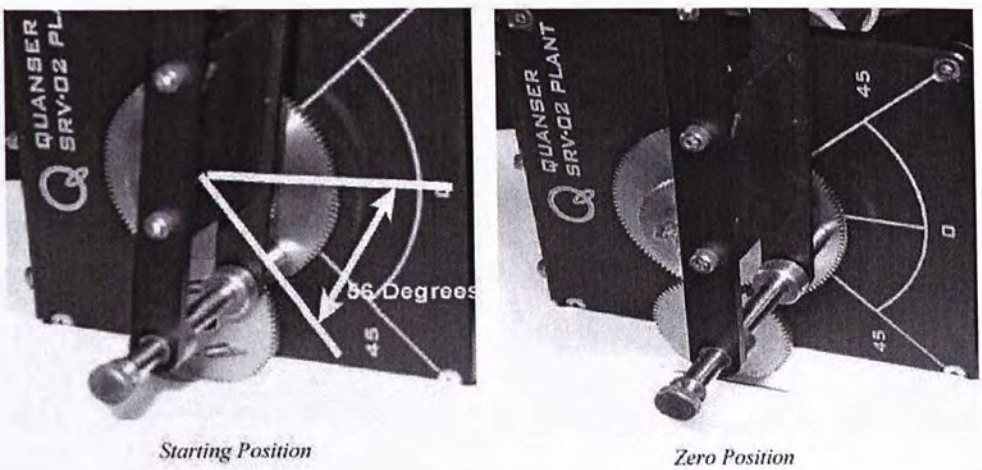

Figure 6.11 Initial Position and Zero Position of Motor

Before implementing the controller, the motor doesn't stay in the zero position but the 56° position shown in Figure 6.11, which is caused by the gravity of the ball and the beam. If the motor does not stay in the starting position, users should initialize the system by choosing the "Initialize" option, and clicking "Apply". It is also suggested to initialize the motor after finishing the experiment.

Step 3: PD controller

To implement the controller, choose the "PID" option, specify the desired ball position, and fill the textbox "K1", "K2", "K3", and "K4" by the designed PD parameters K_{op}, K_{od}, K_{ip}, and K_{id}, respectively, then click the "Apply" button.

For example, we apply the controller using K_{ip} = 7 V/rad, K_{id} = 0.75 Vs/rad, K_{op} = 0.007 rad/cm, K_{od} =0.007 rad s/cm in the experiment, and Figure 6.12 shows the experiment results. In particular, the ball moves to the desired position under an input command, and from the figure we can see the system is stable and the dynamic behavior is as expected.

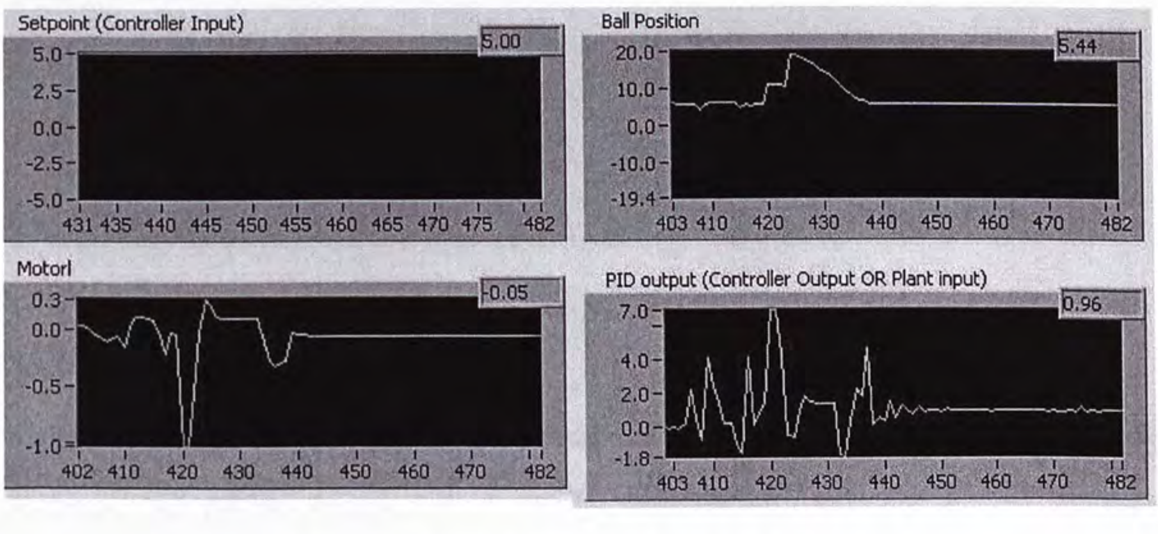

Figure 6.12 Dynamic Behaviors under PD Controller

Step 4: Feedforward controller

To implement the controller, choose the "Feedforward" option, specify the desired ball position, and fill the textbox "K1", "K2", "K3", and "K4" by the designed parameters K_1, K_2, K_3, and K_4, respectively, then click the "Apply" button.

For example, we use K_1= 0.8 V/cm, K_2=0.8 Vs/cm, K_3= 7 V/ rad, K_4= 0.7 Vs/rad, K_4= 0.7 Vs/rad to move the poles of the closed-loop system to

$$(-0.0377+6.7705i, -0.0377+6.7705i, -4.0378, -1.3321).$$

Figure 6.13 shows the experiment results. In particular, the ball moves to the desired position, and from the figure we can see the system is stable and the dynamic behavior is as expected.

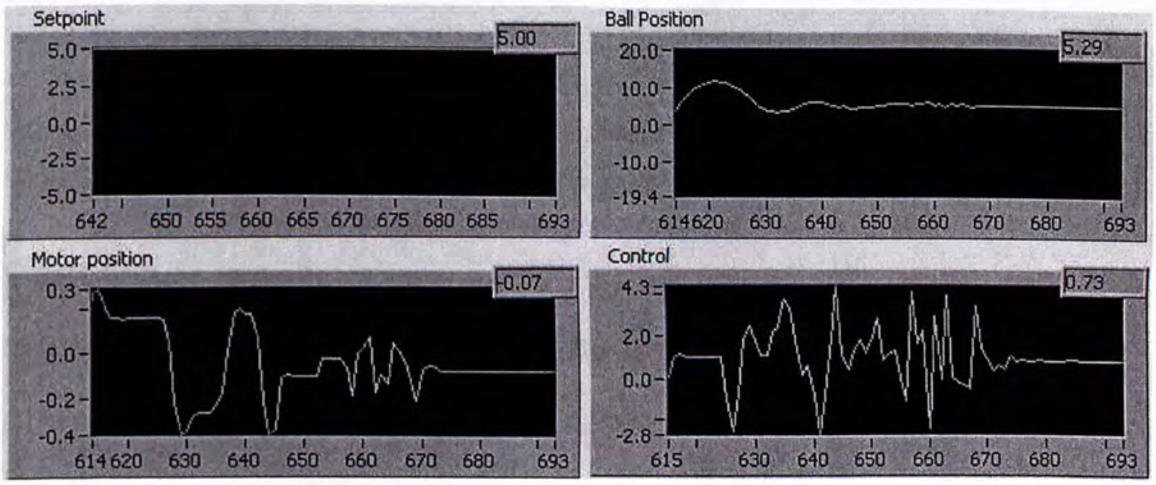

Figure 6.13 Dynamic Behaviors under Feedforward Controller

Step 5: Internal model controller

To implement the controller, choose the "Internal Model" option, specify the desired ball position, and fill the textbox "K1", "K2", "K3", "K4", and "K5" by the designed parameters K_1, K_2, K_3, K_4, and K_z, respectively, then click the "Apply" button.

For example, we use K_1= 0.8 V/cm, K_2=0.8 Vs/cm, K_3= 7 V/rad, K_4= 0.7 Vs/rad, and K_z = 0.1 V/s cm to move the poles of the closed-loop system to

$$(-0.0425+6.7664i, -0.0425-6.7664i, -4.0818, -1.1330, -0.1455).$$

Figure 6.14 shows the experiment results. In particular, the ball moves to the desired position, and from the figure we can see the system is stable and the dynamic behavior is as expected.

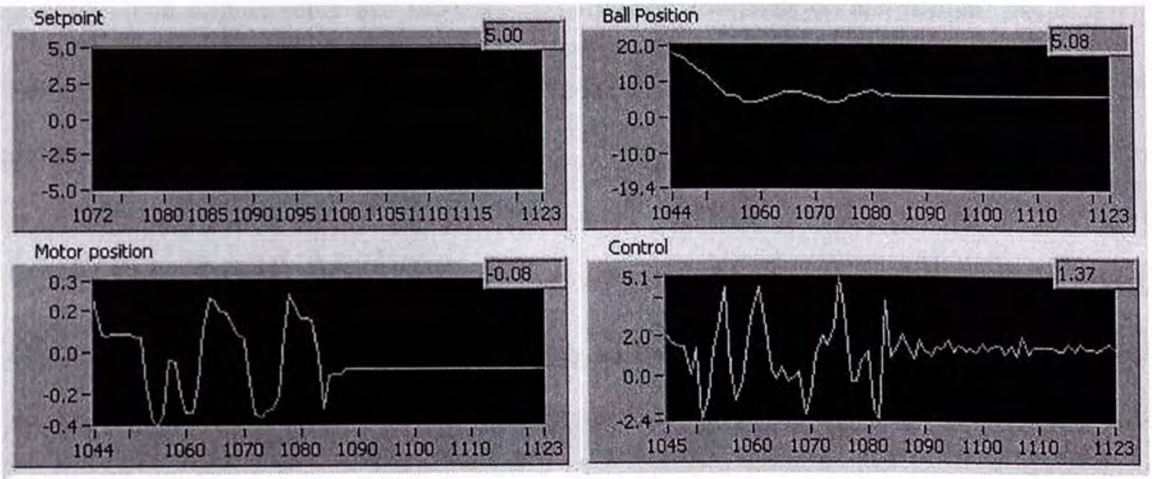

Figure 6.11 Dynamic Behaviors under Internal Model Controller

Step 6: Stop the controller or quit

During implementing the experiment, users can choose "Stop" option to stop the controller. After the experiment, click "Log off" link to quit.

Chapter 7

Education Practice

The feasibility of web-based control laboratory has been practiced at CUHK in the spring semesters of the academic year 2001-02 and year 2002-03 by the third year undergraduate students. The experiments are incorporated into the teaching of the course “ACE 3010 Modern Control Analysis and Design”. This chapter will focus on the education practice and the feedback from the students.

7.1 Practice and Analysis

The application of the web-based laboratory in the course “ACE 3010 Modern Control Analysis and Design” is by a homework assignment. The problem is listed as follows.

Problem: The plant given by $G(s) = \dfrac{K}{s(\tau s+1)}$ *describes the DC motor located in The Applied Control and Computing Laboratory (ACCL) where* $\tau = 0.25, K = 54.75$, *and the output is the position of the motor.*

(a) A feedforward controller of the form $u = -K_x x + Mr$ *has been designed by the tutors where* $K_x = [0.52, 0.23]$. *Calculate M, and Plot y(t) and r=2 in the same figure for* $0 \le t \le 10$ *where y(t) is the output of the closed-loop system.*

(b) *An Internal model controller of the form* $u = -K_x x - K_z z, \dot{z} = e$ *has also been designed by the tutors where* $K_x = [0.01, 0.012]$, *and* $K_z = 0.0015$. *Plot y(t) and r=1 in the same figure for* $0 \le t \le 10$ *where y(t) is the output of the closed-system.*

(c) *Test your design through our Internet Based control Lab (Room 305, MMW) by the procedures shown in online Manual anywhere at any time using a computer.*

Without the web-based control laboratory, students can only complete parts (a) and (b) of the problem. Now, students can also complete part (c) and see the performance of their controller in real situation. Our experience shows that with the help of the online menu, most students can complete part (c) in no more than one hour. Thus, the development of web-based laboratory has enabled the real control experiments to be conducted as if a computer simulation were performed.

We have also sent a questionnaire of ten questions to students, listed below together with the answers.

1. *Does the online menu give you sufficient help?*

Yes: 60%.

No: 40%.

2. *What is the greatest difficulty you have encountered in conducting the experiment?*

In conducting the experiments, the students met some different difficulty basically focusing on the following three points.

(i) Cannot actually relate the theory to practical issue.

(ii) The system is not stable.

(iii) The interface is not friendly enough.

3. Does the computer simulation, say, using MATLAB, give you the same result as that of the real experiment?

Not exactly same but quite similar.

4. If you have observed any discrepancy between part (b) and part (c), can you give any explanation?

Most of the answers focus on the following three points.

(i) The disturbance of the motor is large.

(ii) The friction of points cannot be neglected.

(iii) There is something like friction.

5. Through this experiment, can you compare the performance of the feedforward design and internal model design?

Most of the answers show that the performances are very similar. One student points out that the oscillation in motor position and velocity under internal model design is smaller than that under the feedforward design.

6. Does the real experiment help you understand the classroom materials?

Almost all of the answers are yes. Some of them give the reason.

(i) I can input the parameters with variation so that I can deduce the contribution and the importance of each parameter.

(ii) The real experiment can let us try different parameter values, so that we can understand the material more easily.

(iii) I think it can give us some idea about the real situation.

(iv) It is very interesting to have that kind of demonstration.

7. Do you have any suggestions to improve the Internet-based control lab?

The students give many suggestions, some of which are interesting and valuable as listed below.

(i) Improve the stability of the system.

(ii) If the output result can be stored and be available to be downloaded by user it will be much better.

(iii) Include the principles of the architecture of the system in the manual, so that we know how the system is built.

(iv) Interface should be designed user-friendlier.

8. *How do you compare the Internet-based experiment and on site experiment?*

There are some kinds of options listed below.

(i) Changing parameters is more convenient of on site experiment.

(ii) No time limit in the Internet-based experiment.

(iii) For Internet-based experiment, it can be done anywhere at any time. But the on site experiment is more stable and no network related problem should be considered.

9. *Do you think we should continue to the Internet based control in the assignment for this course, or abolish it?*

Yes: 85%.

No: 15%.

10. *Totally, how much time have you spent on carrying out part c?*

Less than 30min: 19%.

30minitus-1hour: 71%.

More than 1hour: 10%.

7.2 Remarks

Basically, most feedbacks from students are positive. From the feedback, some remarks are summarized as follows.

- **It helps students to understand the control theory and technology more deeply.**

The final objective of the control course is to train students to solve the actual problem in real environment using the theory and technology learned in the class. And the laboratory provides the situation, which can be used not only to test the built-in controllers, but also to test the controllers designed by the students themselves through changing the parameters of the controller online. Thus, this web-based control laboratory not only offers students more opportunities for conducting experiments on person, but also allows the students to explore and create their own designs.

- **It improves students' study interest.**

Many student feel that it is exciting to watch the performance in real time and see the controllers they have designed actually work in the real system. The web-based experiment is more interesting comparing with simulation.

- **It is convenient and time-mobile.**

Since the web-based experiment is available for 24 hours a day, students can perform it anywhere at any time. Also, students can carry out the experiment according to their own paces and schedules.

- **It is important to improve the laboratory.**

Also, many students give some good suggestions on the web-based laboratory. From the suggestions, we realize that, the system stability should be improved, and the interface and experiment manual should be enhanced.

Because only one user can login the system at one time, some students can not login for a long time in the busy period, especially, in the two days before the assignment due. It asks us to design the schedule for the students, for example, allot 3 days for each 5-person group. Thus, it greatly reduces the opportunity of login conflict.

Chapter 8

Conclusions and Future Work

The development of the web-based control laboratory has undergone two phases. And we have made a smooth progress in fulfilling the objectives in the two phases. This thesis is a documentation of our efforts in carrying out the development the laboratory, mainly, the development of Phase 2. In this thesis, we have given a systematic and thorough presentation on the structure, system establishment, experiment design, and education practice of web-based control laboratory.

8.1 Concluding Remarks

- **The phase 1 research is consolidated.**

We have consolidated the phase 1 research through redoing some works, such as reworking the programs, recognizing the database, and so on.

- **More systems are established in the web-based laboratory.**

During phase 2, we have further expanded the scope of the laboratory by establishing two sets of systems, the mass-spring-damper system and the ball and beam system. Together with the DC Motor system and the coupled tank system, built in phase 1 as the prototypes of the web-based experiment, there are four sets of systems in the laboratory.

- **Various experiments are designed on each system platform.**

Based on the fours sets of systems, we have designed various control experiments designed encompassing both classical control and modern control.

DC motor system: Position and speed control by classical design methods such as lead and lag compensation, and PID, and by state space methods such as pole placement, feedforward design, and internal model control.

Coupled tank system: Water level control by lead and lag compensation, PID, and pole placement.

Mass-spring-damper system: Frequency response, Bode gain-phase plots, transfer function, and modeling of the system.

Ball and beam system: Ball position control by PD, feedforward, internal model controllers.

- **The web-based laboratory has been applied in classroom education.**

The DC motor control experiment has been tested in the spring semesters of year 2001-02 and year 2002-03 by year 3 undergraduate students. The experiments are incorporated into the teaching of the course "ACE3010 Modern Control Systems Analysis and Design". Our experience shows that the development of Internet-based laboratory has enabled the control experiments to be conducted in a routine homework assignment and been an effective educational tool for teaching students the basic principle and methodology.

- **The advantages of the web-based laboratory.**

✓ The web-based laboratory overcomes the disadvantages of traditional experimentation, which is time-limited, resource intensive, safe concern, and difficult to organize for part-time students.

✓ The web-based laboratory realizes the integration of theoretical and practical study in science and engineering. And it enhances the learning and teaching quality.

✓ The web-based laboratory has brought the application of the Internet in long distance education to a new horizon and given a new technique to long distance education.

- **The limitations and difficulties of development of the web-based laboratory.**

In general, web-based laboratory is still a newly developed concept as an addition way to enhance long distance education. In developing the web-based laboratory, we met the difficulties such as the delay of transferring data, Internet traffic, network security, and so on. So far, there is another limitation on the selection of the control plants. For example, the plants need to be initialized by hand are not suitable for the web-based laboratory.

8.3 Future Work

- Refine the system in experiment design. Indeed, more experiments can be designed based on the systems.

- To enhance the reality of experiment, it is necessary to reinforce the video system to video/audio system. For example, in some control experiment, a bad controller may produce noise. The audio system will give the true environment to remind the user.

- The systems should be enhanced more stable and the interfaces should be designed friendlier.
- In education practice, we have applied the system in the classroom of undergraduate control course, and we are preparing to use the systems in MSC course, which is a part time program. There are few opportunities for the part time students to use the on site experiment facilities. So the web-based experiments are helpful for their study. Also, we can apply the laboratory in undergraduate final year project. Based on the system prototype built, they can design other appropriate controllers and implemented them by using LabVIEW.

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