AN APPLICATION OF REMOTLEY CONTROLLED EXPERIMENTS TO PERFORM FEEDFORWARD AND FEEDBACK DAMPING CONTROL OF AN ELECTRO MECHANICAL SERVOMECHANISM

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Abstract: This paper presents the findings of a pilot study to examine the possibility of delivering a control and dynamics laboratory session, using equipment located at the University of Leeds, to students at University College London (UCL), utilising the *ReLOAD* (remote access to real experimental equipment) system. The *ReLOAD* system has been developed to provide improved access to experimental equipment, used as part of undergraduate engineering degree programmes. Key to its operation is the availability of the system to serve video clips that record the experiment in progress, providing essential visualisation plus an improved sense of realism for the user. Students at UCL remotely performed an experiment to determine the effect of varying the feedforward and feedback gain on the dynamics of an electro mechanical servomechanism. Evaluation of the *ReLOAD* system, performed by the module leader at UCL, shows the system has huge potential to allow more efficient and collaborative use of laboratory equipment across the global engineering education community.

1 INTRODUCTION

Laboratory based teaching sessions are a key element of teaching engineering during an undergraduate degree program in the United Kingdom. These laboratory sessions provide an ideal opportunity to enthuse, motivate and inspire students through *face-to-face* interaction with teaching staff and real experimental equipment. However these sessions are costly, both in terms of equipment and time taken by teaching staff to deliver them. In the UK, a typical *face-to-face* session may last 2-3 hours and consist of a group of 20-30 students, working in pairs or small groups within a laboratory environment. Often multiple copies of experimental equipment are required for these laboratory sessions, limiting the quality of the equipment that can be deployed. Even with group sizes of 20-30 students, laboratory sessions often need be repeated many times in a given year to ensure all students on a particular program are exposed to the session. Even with multiple copies of equipment and duplicate laboratory sessions, students can find that access to equipment is limited, as often the laboratory is running a different class or teaching staff are attending to other commitments. Students can potentially miss out on laboratory sessions due to illness, or be prevented from repeating a laboratory session to collect more data because of such restrictions. Laboratory sessions can be viewed as being inefficient, since although expensive equipment is used intensively for a period, it may remain unused for most of the year.

In 2000, to overcome some of these limitations, a system called *ReLOAD* (Real Labs Operated at Distance) was developed within the School of Mechanical Engineering at the University of Leeds, which allows access to experimental equipment via a web interface. Although the system cannot be used to develop practical skills such as the use of equipment, it does allow students to develop skills such as planning experiments, collecting and

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analyzing data, and conducting further experiments if required. It offers greater accessibility, can be run 24 hours a day, 365 days a year and allows many students to access a single piece of high quality equipment.

Other institutions across Europe the United States, Australia, Asia etc. are also developing similar systems to allow web based access to experiments, many as part of consortia, to promote sharing of equipment. Like the MIT iLabs system, *ReLOAD* has been used recently to allow students from one institution to use equipment in another, many time zones away. This enables the system to be used at times when normally it would be underutilized. In some of the systems developed, attempts have been made to reproduce *face-to-face* laboratory sessions as closely as possible, in some cases by employing technician staff to be available in the laboratory at a prearranged time, to help conduct the experiment remotely using telecommunication links. In contrast to this approach, *ReLOAD* aims to convince students that this is a physical experiment and not just a simulation, by providing highly visual experiments with the content being visualized using video clips taken from a webcam. It is an important aspect that students should be able to perform the entire experiment, without the need for technician intervention, allowing the experiment to be undertaken at a time that suits the student. This approach is the same as that adopted by the State University of New Jersey (RUTGERS), amongst others.

The *ReLOAD* system is now sufficiently developed to allow the pilot study presented in this paper to be conducted, which examines the system's suitability as an *e-learning* tool. Student feedback has so far been very positive, with students particularly appreciating the virtually unlimited access and the ability to easily visualize the output via the use of the video clips, simultaneously with near real-time analogue data and the reinforcement of the sense that they are accessing real experimental data that these clips provide.

2 RELOAD SYSTEM OVERVIEW

The idea of remote access to experiments is that the physical experimental equipment does not need to be in the same location as the person performing the experiments. Hence a greater flexibility in performing experiments is gained, although there is the danger the user may doubt the realism of the data or feel detached from the experiment being performed no matter how good the interface (Selmer *et al.,* 2005). The Internet or LAN network is ideal for the transfer of data in such cases and though several different methods can be employed to deliver remote experiments, the basic structure adopted here is as shown in figure 1 (Levesley, 2006).

Figure 1 illustrates that a client computer can send a request to a central web server (the *ReLOAD web server*) for experimental data across the Internet from any location with an Internet connection. The *ReLOAD web server* interprets the request and redirects this request via a LAN to one of several *Experiment Server* computers physically connected to either single or multiple pieces of experimental

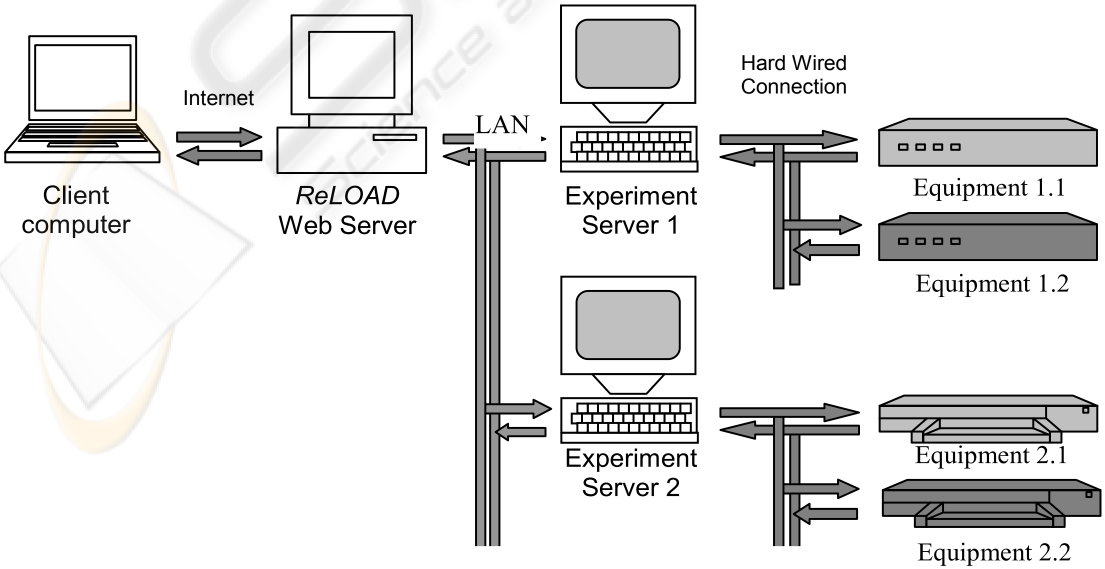


Figure 1: *ReLOAD* Remote Experiment Structure.

equipment. The request is then converted into a series of commands appropriate for the specific equipment being run by the *Experiment Server*. When the experiment requested is completed the *Experiment Server* computer sends results in the form of data images and video clips back to the user on the client computer via the *ReLOAD web server*, providing virtually the same level of information as would be obtained by performing the experiment locally.

2.1 The Web Server

The web sever is set-up to receive and process requests from the client, and since the web server can be a single computer, custom software can be readily created and installed to monitor internet requests. The client computer may be one of hundreds of different PC's and the manner in which data is transmitted and received from the client computer has significant impact on the overall functionality and versatility of the final system. Several alternative methods have been proposed previously. An Active-X control panel could be installed on the client computer to send and receive information (Hites, 2002) through an Active-X enabled browser. Alternatively a Java applet could be created to run on a standard Internet browser to control the experiment (Rohrig & Jochheim, 1999, Sanchez *et al.*, 2000). The *ReLOAD* system simplifies all aspects of the remote experiment to create a reliable, maintainable system. A standard web form is used at the client end to request experiments and retrieve and view the associated results. At the server end, LabVIEW software performs the experiments while monitoring, receiving and sending data across the internet to the client computer. The client computer only requires standard java support to view the video feedback.

2.2 Controlling Equipment

The *Experiment Server* computers perform the experiments and communicates across a LAN and in turn pass the data on via the internet to the client PC. Using data acquisition hardware, LabVIEW software is used to control the experimental equipment. The use of a single programming environment and language simplifies the development process.

The front panel of the *Experiment Server* computer displays all parameters used by the experiment, together with a preview window for the video camera and the results graph. Hence the experiment server computer functions as a demonstration display, allowing staff, students and visitors within the School of Mechanical Engineering in Leeds to observe the experiments being requested remotely. A tabbed panel on the computer displays either a log of the requests submitted to the system or the setup panel. A shutdown button is incorporated into the design such that it ensures that any requests being processed are first dealt with before the ‘shutdown’ state.

2.3 System Communication

LabVIEW allows two alternative methods to communicate the required information between computers to perform remote experiments LabVIEW HTTP Server with Common Gateway Interface (CGI) Scripts or embedded ActiveX control panels.

The LabVIEW Web Server and embedded panel method has several shortcomings. Firstly, it would be necessary to purchase as many licenses as the number of users that may be expected on the experiment. Secondly, the provision of video; since continuous experimental interaction is possible it would be consistent to use streaming video footage, giving a ‘live’ indication to the state of the experiment. However, the quality of the video footage is dependant on the connection speed. Finally, this method relies on proprietary plug-ins in order to embed the VI’s panel in a web-page.

The HTTP Server with CGI scripts method does not encounter these problems, and justifies its use for this application. The HTTP server does not require a license dependant upon the number of users expected and only a widely supported, multi-platform java plugin is required, in this case to display the video. It is important to note that only experiments not requiring *continuous* interaction are possible using this method.

The LabVIEW Internet Toolkit, an add on to the standard LabVIEW package, provides a HTTP server and a set of related Virtual Instruments (VI’s). VI’s is the term used to refer to units of code that perform a particular function. Of particular relevance to this application are the CGI script VI’s. CGI scripts are typically used in association with a form on a web-page. Forms are defined using standard HTML elements and allow a user to enter information into a number of fields and post it to a server. The server receives the post and invokes the relevant CGI script. The script then processes the information and sends back a response, typically a web-page, through the server to the user. Note, once the user has posted a form the web-browser will

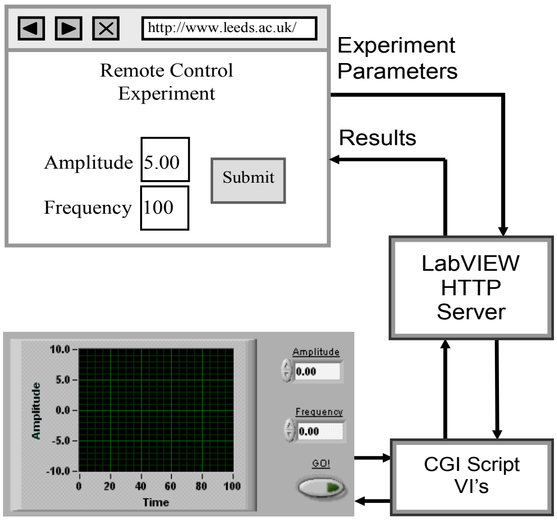


Figure 2: 'Labview HTTP server with CGI script' method.

await a response from the server and display it once received.

It is possible to achieve the required interaction between the user and the experiment by combining the LabVIEW HTTP Server and the CGI script VI's. The experimental parameters can be entered into a form on a web-page and posted to the LabVIEW HTTP Server. This will then invoke a CGI script VI that interprets these parameters and uses them to conduct the experiment. The results will be returned in the form of a web-page to the user when the experiment is complete. This approach is illustrated in figure 2. The CGI script VI's can only be used in conjunction with the LabVIEW HTTP Server. The communication between the web browser and HTTP Server can be over any network supporting HTTP traffic, for example a departmental LAN or the Internet. LabVIEW (8.0) contains tools aimed at making it easier to control VI's using a web-browser. The front panel of a VI can be embedded into a web-page. It takes the form of an ActiveX component if Internet Explorer is being used, or a plug-in for Netscape. The computer running the VI must also run the LabVIEW Web Server which controls communication between the embedded front panel in the web-page and the actual front panel of the VI. The user can view the front-panel or request to control it. When viewing, the user sees a 'live' representation of the front panel. When controlling, the user can do everything that would be possible if using the actual VI, for example altering controls or pressing buttons.

2.4 Experiment Request Control

As each experiment conducted will take a finite amount of time, and multiple requests may be submitted by different users at an instance in time, a queuing system is used to ensure all experiments are performed in an orderly manner.

Both incoming experiments and outgoing results are stored in queues. When the server receives data posted from the 'input parameters' web-page it is added to the back of the request queue. When the experimental apparatus is ready to conduct an experiment it removes the oldest request from the queue and uses the parameters given. The experiment results are placed at the back of the results queue once the experiment is completed. Both queues operate on a first in first out basis. Each item in the request queue contains a number of elements. Firstly are the IP Address that the request was submitted from and the CGI connection information, such that the results can be sent back to the user. The experiment name is sent as a text string to provide for the possibility of running multiple experiments on the same machine.

Finally, the parameters sent from the web-page form are included as a keyed array. This is a cluster of two arrays, the first containing the parameters names (called keys) and the second their values. The 'keys' are simply the names given to the individual fields in the web-page form. Each item in the Results queue consists of two elements. Firstly the CGI connection information required to send the results back to the user. Secondly, a text stream containing the results web-page location.

The queue size is limited to prevent large numbers of requests amassing under heavy demand. A default value of 10 was used for the maximum number of requests in the queue, an acceptable compromise between allowing multiple users and minimizing the delay before results are returned. If the queue is full when a request is submitted, the user is sent a 'busy' web-page in reply, the request is then discarded. A further check can be performed to check if the IP address of a submitted request is the same as one currently in the queue. If this is the case the request is discarded and a single user is prevented from dominating the queue system.

3 EXPERIMENTAL EQUIPMENT

The experiment chosen for this pilot study of *ReLOAD*, to be remotely delivered to students on E467 *Automatic Control* at UCL, was one which enables investigation of the performance of a closed loop position servomechanism, as the forward path gain and the velocity feedback gain are varied. The purpose of the servomechanism system is to keep the angular position of the *Output* shaft (output dial) in correspondence with that of a *Reference* or *Demand* shaft. The purpose made equipment, used for the remote experiment was designed and built by staff and students of the School of Mechanical Engineering at Leeds and is based on equipment used in *face-to-face* laboratory sessions in the second year of an undergraduate degree programme. It comprises the Servomechanism (motor, position potentiometer, tachogenerator etc) and Controller. Figure 3 shows photographs of the original *face-to-face* equipment (upper photograph) and the adaptation of the controller (lower photograph) to allow its use as a *ReLOAD* experiment.

A block diagram for the experimental system is shown in figure 4. When a voltage *Demand* or *Input signal* is applied to the system it passes to the *Forward path potentiometer* with variable gain K_a, set by the user. The signal is then sent to an amplifier which is then applied to the motor. A tachogenerator measures the velocity of the motor; within the VI the magnitude of the velocity feedback is calculated dependant on the value of a gain K_t, set by the user. The position of the motor is measured via a potentiometer, with gain K_p. This experimental system allows the user to vary the forward path gain, K_a, and the feedback gain, K_t, and observe the response of the system in terms of position and velocity of the servomechanism, hence illustrating important control concepts. The magnitude of the position feedback gain is kept fixed at 1 and can not be altered by the user.

The experiment control software used was LabVIEW 8.0, the internet server software was LabVIEW HTTP server 8.0. and the experiment server was a Pentium 4 cube PC.

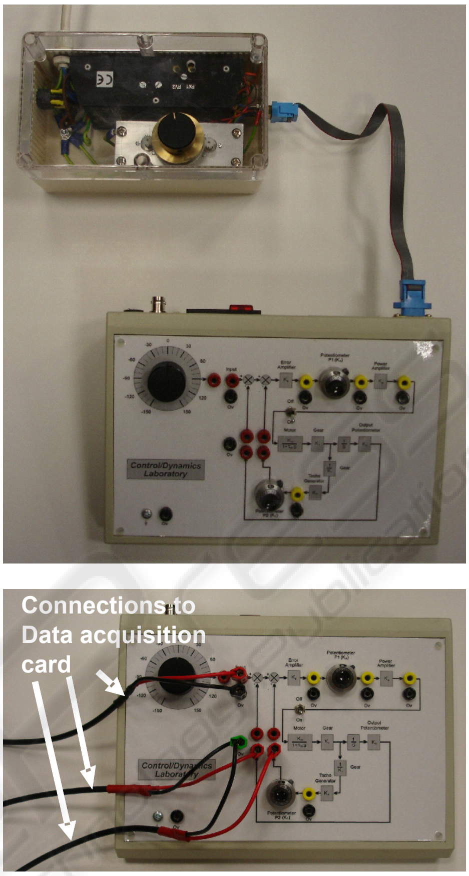


Figure 3: The *face-to-face* experimental rig (upper) and adaptation for the *ReLOAD* enabled version (lower).

4 THE CLIENT COMPUTER

The only requirement for the client computer is that it has appropriate Internet browser software installed, as only relatively small amounts of data will be sent to the *ReLOAD* web server. Upon entering the experiment internet address, the user is

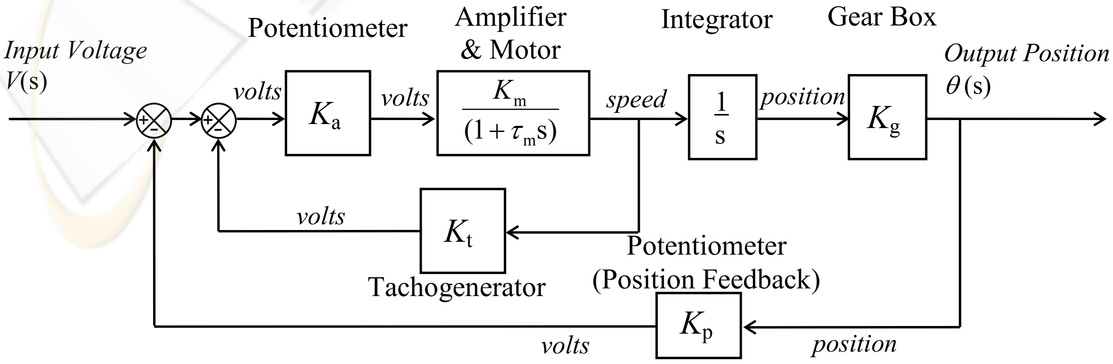
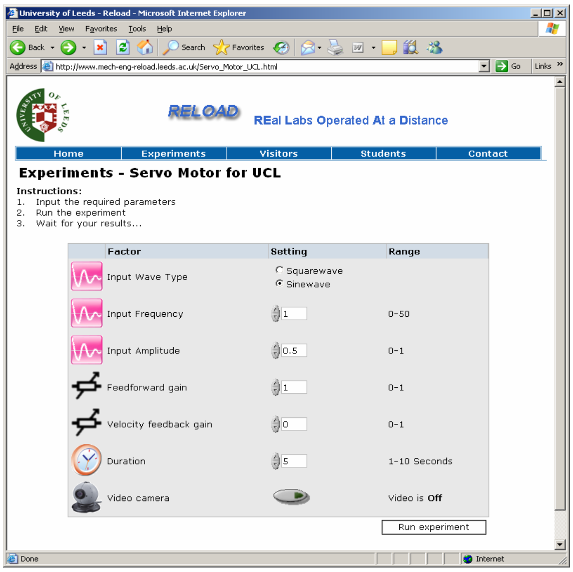


Figure 4: The experiment block diagram.


University of Leeds - Reload - Microsoft Internet Explorer
File Edit View Favorites Tools Help
Back Search Favorites
Address http://www.mech-eng-reload.leeds.ac.uk/Servo_Motor_UCL.html
Go Links
RELOAD
REal Labs Operated At a Distance
Home Experiments Visitors Students Contact
Done
Internet

Experiments - Servo Motor for UCL

Instructions:
1. Input the required parameters
2. Run the experiment
3. Wait for your results...

Factor	Setting	Range
Input Wave Type	○ Squarewave ● Sinewave	
Input Frequency	1	0-50
Input Amplitude	0.5	0-1
Feedforward gain	1	0-1
Velocity feedback gain	0	0-1
Duration	5	1-10 Seconds
Video camera		Video is **Off**

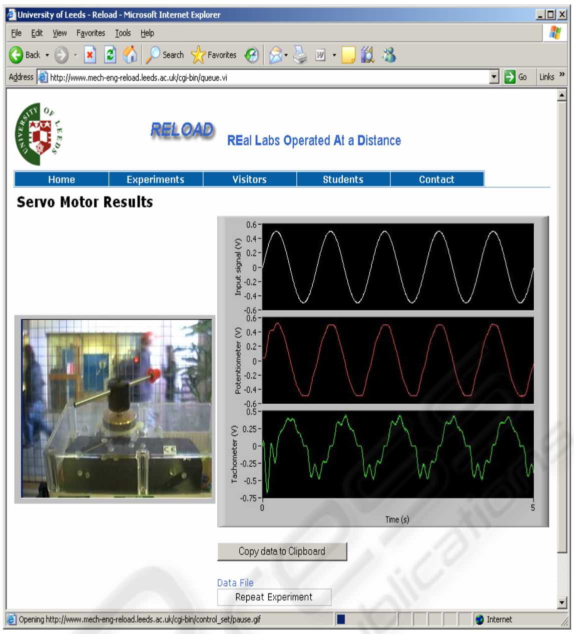
Run experiment

Figure 5: The Parameter Input Web-Page.

presented with the *Parameters Input* web page as shown in figure 5.

A standard HTML form is used to submit information to the *ReLOAD* Web server, with parameters entered into the text boxes, and submission activated using the submit button. Usually a submit button will directly post the information in a form to the defined address. However, to prevent the user repeatedly pressing the submit button, a java-script function first checks to see if the user has already pressed the submit button. The form will be submitted only if the function returns a Boolean 'true'. Note it would be possible to remove this java script and use the server computer to delete duplicate experiment requests.

The results web-page presents the results from the experiment to the user in a number of ways. A graph is displayed showing the input signal to the servomechanism, its displacement, via the voltage output from a potentiometer, and its velocity, represented by the voltage output of a tachometer. An embedded video clip of the experiment and a set of standard controls allowing replays, rewinding and fast-forwarding are also displayed. The video is displayed using a java applet providing a consistent experience across different browsers and does not require the user to download any special plugins. A link to the results Comma Separated Values (CSV) file is provided allowing them to be imported into spreadsheet applications such as Excel and a copy to clipboard function is also included, which serves a similar purpose. The results web-page is shown in figure 6.


University of Leeds - Reload - Microsoft Internet Explorer
File Edit View Favorites Tools Help
Back Search Favorites
Address http://www.mech-eng-reload.leeds.ac.uk/cgi-bin/queue.vi
Go Links
RELOAD
REal Labs Operated At a Distance
Home Experiments Visitors Students Contact
Input signal (V)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Potentiometer (V)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Tachometer (V)
0.5
0.25
0
-0.25
-0.5
-0.75
0
5
Time (s)
Copy data to Clipboard
Data File
Repeat Experiment
Opening http://www.mech-eng-reload.leeds.ac.uk/cgi-bin/control_set/pause.gif
Internet

Servo Motor Results

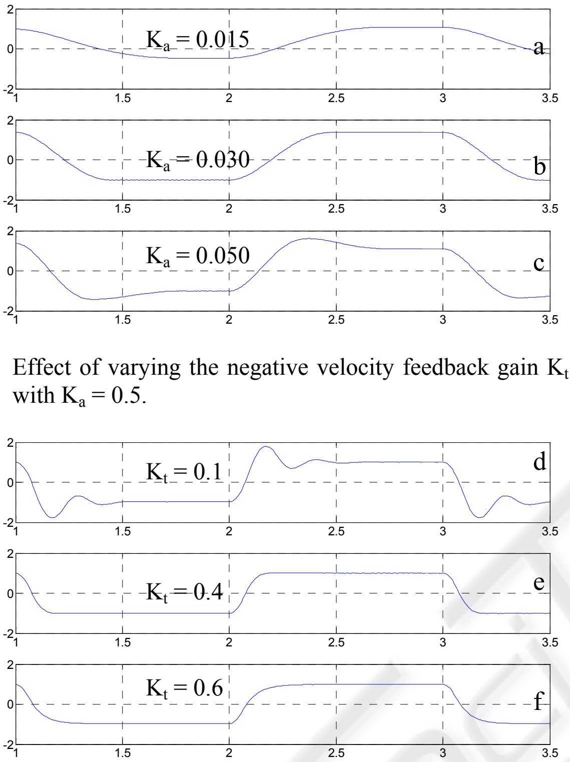
Figure 6: The Results Web-Page.

5 THE EXPERIMENT

Both the *face-to-face* and *ReLOAD* delivered experiments involve two components both utilising a square wave input signal to drive the servomechanism. The *ReLOAD* interface enables the period of time over which experimental data is collected to be set as well as the option of a video clip captured using a standard USB webcam (60fps 320x240). Visualisation of the servomechanisms motion is a crucial component of understanding the mathematical parameters used to characterise dynamic systems.

The first component of the experiment investigates the effect of varying the forward path gain, K_a, with no velocity feedback, that is K_t set to zero. The user is required to determine the magnitude of K_a which gives the fastest possible settle time, that is the critically damped state. The user then chooses two values of K_a above and two values below this critical state and repeats the experiment. The user should observe that as K_a is decreased below the critical value, the settle time increases, there is no overshoot and the damping is greater than one. Whilst as K_a is increased above the critical value the settle time and overshoot increase whilst the damping decreases. Students should observe that varying K_a does not alter the magnitude of the steady state gain. Figure 7 (upper three graphs) illustrates the response of the servomechanism system, in terms of displacement, to increasing values of K_a when K_t is zero. The figure shows two and a half seconds of data with the first second omitted so as not to show the initial transient state exhibited by the system, hence enabling a clearer comparison.

Effect of varying the forward path gain, K_a, excluding negative velocity feedback, $k_t = 0$.



Effect of varying the negative velocity feedback gain K_t, with $K_a = 0.5$.

Figure 7: The servomechanism response to variation of the forward path and feedback gains.

The second component of the experiment investigates the effect of varying the velocity feedback gain K_t with the forward path gain, K_a, set to a magnitude of 0.5. The user is required, as in the first component, to determine the magnitude of K_t which gives the fastest settle time without any overshoot, the critically damped state. The user again chooses two values of K_t above and below and the critical state and observes the percentage overshoot, settle time, frequency of oscillation and damping ratio. The students should observe below the critical damped state as K_t is decreased the level of damping decreases, the settle time, overshoot and the frequency of oscillation increase. Whilst as the magnitude of K_t is increased above the critical value the level of damping increases, the settle time increases and there is no oscillation and the settle time increases. Figure 7 (lower three graphs) illustrates the response of the servomechanism system, in terms of displacement, to increasing values of K_t when K_a is set to 0.5.

6 EVALUATION

The particular remote experiment described in this paper has been used successfully since 2005 as an alternative to an almost identical *face-to-face* version of the Position Servomechanism experiment. During 2006 the *ReLOAD* Position Servomechanism experiment was utilised by number of students at UCL School of Mechanical Engineering as part of an assignment.

A servo-motor lab has run at UCL for at least 20 years; 6 sets of experimental apparatus were originally purchased, and these have been used by groups of 2 or 3 students at a time. Since its original purchase, the experimental procedure had become somewhat outdated: students were asked to change gains on the controller by interchanging large wire-wound resistors. Considerable time has been required to set up the experiments and return them to storage each year, in addition to the regular maintenance required to repair natural wear and tear. In 2006 there was a further pressure of space, as the control laboratories were being refurbished and refitted. The combination of these factors meant that the internet-based laboratory was a very attractive alternative.

Compared to the traditional laboratory experiment, the internet-based version has been continually updated in order to demonstrate the most current experimental procedure – this was tailored to be specifically appropriate to the particular course being taught.

Operating over the internet gave students the flexibility to study alone or in groups. The lecturer offered a “surgery session” in a computer cluster, after a scheduled computer-based class where students had the opportunity for personal feedback and guidance in running the experiment. The queuing system described above worked flawlessly, and the brief duration of the experiment (approx.10 seconds) meant that students rarely had to wait more than 20 seconds for their results.

Outside this scheduled session, the system had the benefits of increasing available experimental time for the more interested students, and also increased participation among the less-motivated students. The experiment was available over the

Christmas holiday period, and this gave an opportunity for students to repeat and check their results as they wrote their reports. Students particularly appreciated this opportunity to act on feedback and guidance from their tutors before submission of their reports.

An important aspect of the evaluation of this form of remote experimentation is whether the learning outcomes of those students undertaking the experiments remotely are different form those undertaking *face-to-face* experiments. A study to investigate this in detail, would need careful design to ensure valid comparison. To date, the experiments performed at UCL and Leeds, though using the same basic equipment and sharing the same broad objectives, have been tailored to the individual institution's curriculum needs. This has resulted in a the two institutions setting different learning objectives for their sessions. This in some way illustrates the flexibility of the *ReLOAD* system, but makes a comparative study problematic. Further experiments using this system are planned, that it is hoped will allow this type of direct comparison to be made.

7 CONCLUSIONS

This paper has illustrated the operating principles of the *ReLOAD* system in general and for the remote delivery of a position servomechanism experiment, taught *face-to-face* at The University of Leeds, to a number of students at University College London. The pilot study has proved the efficacy of the *ReLOAD* system, with both students and lecturers finding a useful educational tool.

Further development of the *ReLOAD* system is underway with a view to improved visualisation and the delivery of alternative experiments using the same experimental equipment, alongside the development of new equipment. Furthermore, the Higher Education Academy Engineering Subject Centre has provided funds to build a demonstration area of the *ReLOAD* website to raise awareness amongst UK academics of this new mechanism for delivering experiments. This will include an interactive section and teaching materials developed for use with the experiment.

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