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A Virtual Laboratory Experience Based On A Double Tank Apparatus

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Abstract

How can a virtual laboratory experience achieve the typical educational outcomes expected from a normal in situ laboratory experience? This paper deals with this question in the context of a double tank apparatus experimental set up. For this laboratory experiment a world wide web interface was developed to assist students in assimilating control engineering concepts at the University of Melbourne.

Keywords Laboratory experiments, www delivery, virtual laboratory, control engineering education

1 Introduction

In engineering the laboratory experience is an integral part of the educational process. The experience with instrumentation, setting up a laboratory, performing experiments, interpreting data and fitting it into a theoretical framework for computation and finally interpretation is essential. The whole process is aimed at providing the student with training in being able to quickly focus on the important aspects of a particular situation, with the aim of establishing an appropriate abstract framework for analysis and design. Ultimately, the outcome of the experiment demonstrates to the student the validity (or otherwise) of the approach taken.

In the context of control engineering education, the double tank apparatus (or similar) is a popular vehicle for such an experience. The double tank apparatus has relatively slow dynamics, exhibits a number of interesting non-linearities, in both actuation and measurement as well as dynamics. It is therefore well suited as an introduction to both system identification and system control. The simple physical principles it illustrates make it suitable for all engineering students studying control, be it from a chemical, mechanical or electrical engineering perspective.

Presently, there is a lot of activity in trying to use the internet for the delivery of educational services [1],[2],[3],[4]. Its ability to distribute information to anywhere, anytime is indeed attractive. Of course there is a huge difference between knowledge and understanding, between serving information and teaching, and learning for that matter. So how can we exploit the present fantastic telecommunication power to assist students to learn, to gain experience, to actually deliver education?

For related work using similar apparata for control engineering education we refer to see [2],[3], [4] as well as the other papers in this invited session at the CDC 2001.

Our experience in delivering a laboratory experiment based around a double tank apparatus described in this paper is a first attempt at the University of Melbourne to explore the issues of how a "virtual" laboratory experience can be used to achieve the typical objectives of an engineering experiment.

The paper is organized as follows. The next section describes the physical set up and the interface environment. Then we describe the web page environment that the student can access. We conclude with observations about the educational aspects of the set up. Advantages and disadvantages as compared to a normal in situ laboratory experience are described.

2 The experimental apparatus

The double tank apparatus is the Coupled Tank Control Apparatus PP-100 (see Figure 1) produced by Kent Ridge Instruments, Singapore [5]. It is a two-input two-output system. Each tank has an inlet commanded through a voltage controllable pump and an outlet that can be adjusted through a manually controlled valve only. The outlets communicate to a reservoir from which the pumps extract the water to deliver it to the tanks. The set up is such that any spill over (a tank overflowing) is automatically redirected to the reservoir. The tanks are connected through a baffle valve, which again can only be adjusted manually. So for the sake of remote control, the configuration consists of fixed positions for both outlet valves and the baffle valve. The tank pump control is a voltage level in the

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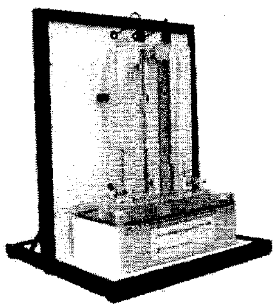

Figure 1: Double tank apparatus

range 0 to 5V, where these correspond to the pump not operating at all, and full power respectively. Yet in order to achieve waterflow, a minimum of (about) 1.4V is required to overcome the head, which makes the effective control range 1.4V to 5V. The outputs received from the apparatus are the water levels in the tank. The level can vary between 0mm (empty) to 300mm (overflow), which is translated through the capacitive transducer into a DC voltage ranging from 0V (empty) to 5V (overflow). The real minimum water level that is actually achievable (because of positioning of tubes and valves) is about 17mm of water, which corresponds to 0.3V. This makes the effective measurement range 0.3V to 5V.

The analog transducers signals are read through a data acquisition card and stored on the host PC into a simple ASCII file, ready to be used by Matlab or Excel. Matlab and Excel are available on the local PC. Matlab is used to control the tanks. Excel is used as a simple data base interface for all the experiments performed. It also provides some low level graphics capability for viewing of raw data. The same data acquisition card has analog output signals that can set the voltage levels for the pumps. The low-level data acquisition and data control is effectuated through a DaqBoard/2000, which takes up one PCI slot in the host PC (in this case a Pentium III).

The dynamics are relatively benign, typical time constants are in the range of ten to fifty seconds. This allows for sample periods of about two seconds, which in turns provide ample time to let the host computer use Matlab to compute the relatively simple control actions in the loop and interact with the DaqBoard/2000 to command the pumps. The same host PC also runs a web server program Xitami, which enables remote control through the internet. It runs local scripts communicating with Matlab and the hardware as required, and passes information onto a trusted www server, who relays the information to the end user. A separate web server must thus be available for the web interface.

Most importantly notice that there is no camera available. So there is no visual inspection of the actual apparatus, and its condition, through the www interface. (Technically this can be provided of course at relatively low cost.)

3 Typical experiments

3.1 Model, prior knowledge

The first task in any modern control design process is to obtain a model. Simple system identification techniques can be taught and experienced using the coupled tank apparatus. In its standard configuration, three different situations can be modeled, two options for only one pump available for control (the other pump off) and one option in which both pumps are available for control.

Because of the physics of the system, the actual system dynamics are mildly non-linear. The outflow through the direct outlet valves will be related to the square root of the height of water in the tank, and the flow through the baffle is roughly proportional to the square root of the difference in water levels in the tanks. Furthermore the physical constraints mean that essentially inputs and outputs are all subject to saturation.

Given a particular operating point, say mid range for the pump voltages (3.2V), a linear system model can be obtained from collected data using the system identification toolbox in Matlab [6] [7] [8].

Identifying the water level, as measured through the output voltage of the transducers as y_k, $k = 1,2$ for tank k and the input voltages to the pump motors as u_k, an approximate physical model can be proposed of the form.

$$\frac{d}{dt}\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} -a_1\sqrt{y_1} + b_1 u_1 \\ -c\ \mathrm{sign}(y_1 - y_2)\sqrt{|y_1 - y_2|} \\ \hdashline -a_2\sqrt{y_2} + b_2 u_2 \\ +c\ \mathrm{sign}(y_1 - y_2)\sqrt{|y_1 - y_2|} \end{pmatrix}. \quad (1)$$

The coefficients a_1, a_2, c, b_1, b_2 are positive and determined by the valve characteristics and generally the geometry of the tanks. The dynamics of the motor, pumps and transducers have been neglected; which is not unreasonable in view of the inertia of the tanks.

The above model is linear in the parameters, and data collected can be used to estimate these directly. Alternatively, a linear system model structure for system identification purposes can be proposed as:

$$\begin{pmatrix} Y_1 \\ Y_2 \end{pmatrix} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \begin{pmatrix} U_1 \\ U_2 \end{pmatrix}. \qquad (2)$$

Where the transfer functions T_{11} and T_{22} are first order,

$$T_{kk} = \frac{q_{0,k}}{1 + p_{1,k} z^{-1}},$$

and the off-diagonal transfer functions T_{12} and T_{21} are second order

$$T_{km} = \frac{q_{0,km} + q_{1,km} z^{-1}}{1 + p_{1,km} z^{-1} + p_{2,km} z^{-2}}.$$

More completely, one could also include the saturation nonlinearities in the above in an obvious manner.

3.2 Modeling experiments

A model building exercise goes through a number of stages. First one needs to select an appropriate sampling time. Then an appropriate experimental condition has to be generated as to obtain significant data to identify a plant model which can be used for simulation and or control. A typical experiment script for performing this task in situ with the above apparatus could read as follows:

- Perform a number of step tests, varying the step size input from 1V to 2V, e.g. a step from $u_1 = 2.6V$ to $u_1 = 3.6V$ and a step from $u_1 = 2V$ to $u_1 = 4V$. Determine from the response graphs a dominant time constant and appropriate sampling period.
- Design a pseudo random input consisting of a symmetric block wave (amplitude 1.5V) with randomly varying block length. (Choose the mean block length to be comparable to the time constant of the system.)
- Collect data, inputs and outputs and construct a model using 75% of the collected data.
- Validate the model obtained against the remaining data.

A more comprehensive script could include a task like fitting a model of the form of equation (1) to the data, which involves a more demanding optimization task.

3.3 Control design experiments

A very typical control task for the double tank apparatus is level control. In single pump configuration only one level can be regulated. The more demanding task is of course to regulate the downstream tank, eg. control y_2 from u_1 using only measurements of level y_1. But any other combination of regulated variable, control input and measurement variables is of course feasible. Each of these control configurations presents the students with a different control task, and in particular different limitations.

In the two input mode, both water levels can be regulated. More demanding and more interesting control objectives could be to track a given reference water level.

The variants are of course many, but a typical design experiment script for a first course in digital control could focus on:

- design of a PID regulator (single pump control, single measurement)
- design of a non-interacting PID regulator (two pump control, two measurements)
- linear state feedback (single pump control)
- linear state feedback (two pump control)

To this end the student may be presented with a validated linear model (a submodel of the form (2)) identified using an identification experiment, and be asked using a design environment to come up with a particular controller. The controller can then be implemented and tested first against the model and subsequently on the laboratory set up. The main exercise here is of course to understand the limitations of a particular design strategy. How does PID compare with linear state feedback, observer based design versus linear state feedback and so on. Also, students can get a feeling for how to translate model knowledge, physical system understanding and its limitations into realistic control objectives. (e.g. One should not attempt filling tank 2 from pump 1.)

In a more advanced setting, students could design a feedback linearising control, a nonlinear observer and apply different robust design techniques. This is not the issue here. The essence of the laboratory experience, either for the system identification or control task, is that a physical system is available on which certain methodologies can be tested. *The issue is thus the availability of (real)data and access to a real-time implementation of a particular control strategy. Neither of which require the student's presence.*

4 The web interface

The web interface provides a very convenient way of presenting students with a lot of information in a very structured manner. Information about system identification, experiment design and control design can all be co-located in a convenient format. The site can be structured such that the information is available at different levels of depth of understanding, catering for the beginner as well as the more advanced students in a seamless way. Design, simulation tools and hardware access can all be controlled through the same interface. This is of course the main appeal of the web in delivering a laboratory experience from the convenience of your preferred computer location.

In the design for our web interface the following assumptions were made:

- the personal desktop is a lean client (no simulation or design software tools on the client machine),
- a high bandwidth network is available (the University LAN network generally offers 100Mb/s to the desktop),
- no particular browser requirements are to be imposed (no special browser software required).

This is a fairly restrictive set of assumptions, but one that would ensure simplicity of use, least access troubles, and the fewest complaints from the users (apart from those not having the high bandwidth access), and thus would enable one to focus on the real essential items.

The assumption of a high bandwidth network is somewhat restrictive, but it is only required for the simulation/design stages of the learning experience. The actual control implementation and experiment execution does not rely on the speed of the connection. So, provided the user has a lot of patience, even slow modem access would suffice.

The items to be provided on the www host are thus

- General information about the experimental apparatus, its limitations and design specifications, including general information about the type of experiments that can be performed.
- Simulation software, allowing users to interact with a simulated apparatus in a reasonable realistic manner, without needing to perform actual experiments. Driving the simulation software will be through a scenario specification page.
- Design software, with a simple query interface, through which the user interacts with the software.
- Access to hardware control and identification experiments, which can be modified and personalized through an appropriate query interface.
- General security and access control software, to avoid conflicts in usage and unauthorized access.

Additional items made available on the www host are:

- A user identification page, which allows users to build up their own profile of using the equipment as well as providing a facility through which the instructor keeps track of the progress of the user.
- Quiz and test facilities, with automated marking, and feedback to the student/users.
- General feedback and query software.

The programming environment in which the above was realized uses HTML and Java programming for the interface and user interaction part. CGI files /Perl programming are used for interacting with host software, C++ (used for running the simulations), Matlab (used for system identification and control design software) as well as interfacing with the DaqBoard/2000 hardware and software and Matlab in real time control mode. The complete site is controlled through the web server program Xitami, running on a Windows platform. According to University specifications, the interface was made in as much as this is possible browser independent. The site is restricted to authorised users. In particular security issues identified with the use of CGI files and Perl scripts disallowed the site to be one of general access, and restricted access behind a firewall was imposed.

As indicated, no video or audio feedback from the experimental apparatus to the remote user is provided at present.

Detailed implementation information can be obtained from [9]. Let it suffice here to observe that the main advantage of the www interface is that it provides access to

- real data from user own defined experiments for identification purposes.
- remote control implementation interface.
- data from closed loop control experiment for further analysis.
- a simulator, a virtual double tank apparatus.
- general information about the apparatus, system identification and control operation.
- on-line self test quizzes, evaluation software.
- data base of past experiments, with the corresponding measurements.

The simulator and general information environment are a crucial part of the www interface. In this way a large number of users can (simultaneously) gain experience about the behaviour of the double tank apparatus before attempting an actual experiment with the laboratory set up. Indeed from an educational point of view, it was perceived that a lot of the elementary errors and first system identification as well as control designs could all be tested on a virtual lab, rather than the real laboratory apparatus. The simulation package (running in $C++$) provides the user with data that can be used for both system identification as well as control design verification. The simulation is reasonably realistic in that it simulates the behaviour well over a range of operational conditions, but it does not cover the complete behaviour of the actual apparatus. Once the user is satisfied that the design works in a satisfactory manner against the virtual equipment, an experiment using the actual double tank apparatus can be performed.

5 Educational objectives?

If the main educational objective for the control/system identification experiments is to allow the user through experimentation to obtain an understanding of limitations of hardware and to gain an appreciation of the limitation of models and control, than it is our opinion that little is lost through a remote experiment as compared to an in situ experiment.

Indeed, whether the data are collected through a network, or simply through a digital acquisition board into the host computer is not a substantial difference (a matter of distance and a few protocols). Similarly, for control design, selecting parameters to be downloaded through a www interface or simply setting parameters on a Simulink block is again not that different.

The essence and the value of the experimental apparatus in this context is merely to be a vehicle for data collection of a physical system's behaviour. The user's presence is irrelevant in this exercise. In the end (physical) data confirm or disprove the student's control/system identification designs, and that is how control/system identification learning is achieved.

In this process, the virtual double tank, the simulator, is probably the next best thing. It provides near real behaviour and for a first contact with system identification and control design, it could even suffice. In essence a completely virtual lab (dispensing with the hardware) could achieve most of the educational outcomes that are typically envisaged in a simple system identification/control experiment.

Because we can collate into one organized and easily navigated environment all relevant information, the www solution is arguably the more convenient environment to deliver this learning experience. From this perspective, the network is irrelevant; it merely provides the flexibility of location.

On the other hand, it is of course entirely possible that the experimental set up is there to teach the student not only the above, but also about transducers, interfaces and protocols. In this case, the above solution is not going to provide the desired outcome. Indeed in the above implementation, all the low level interfacing and interaction between different software and network environments is completely transparent to the end user. This is not to say that such experience cannot be accommodated in a remotely directed experiment, but it requires a completely different set of tools and transducers to make this feasible.

Finally let us observe that the in situ experiment has some additional flexibility. Here for the double tank experiment, the external conditions, the leak valves for both tanks and the baffle valve joining both tanks are fixed in the remote experiment. (A truly virtual environment, does not suffer from such constraints.) In situ, these can be easily changed to illustrate yet another level of disturbances or robustness of design. This experience can of course also provided in remote mode at the expense of some further actuation and instrumentation. However this does not substantially alter the picture. In a similar vein, visual and audio feedback is lacking at present through the remote control mode. Notice that this is not an essential feature in the educational process, but if desired it can be added relatively straightforwardly.

6 Final observations

Laboratory experiments in system identification and control can benefit from a www based implementation in that it can provide a streamlined, single point of contact in a largely automated environment. The tools to do so, although readily available, are not standardized and require still low level programming. This leads no doubt to a duplication of effort and a plethora of different implementation strategies around the world. The most useful addition as far as the educational experience goes is the virtual apparatus, the simulator. Although not completely realistic, it can achieve most of the educational outcomes that are envisaged.

In general, the investment, in development and implementation, of a www based virtual laboratory, linked to an actual laboratory apparatus is not insubstantial. The return is a more flexible somewhat more rewarding learning experience for the students, which is easily monitored by an instructor. (The data base facility incorporated in the set up makes it possible to track progress, usage and users over extended periods of time.) The added flexibility of time and location is a minor one in terms of resource allocation and usage, in particular if restricted access is implemented.

Maintenance and continuous improvement is a relatively straightforward task, but it requires a great deal of discipline and should not be approached lightly. In particular maintenance of *excellent, detailed* documentation is essential. This task should not be underestimated. Many implementation details are dependent on particular software solutions. As software platforms change, this needs to be maintained and software needs to be updated as required. In the Melbourne implementation, some of the software that requires continuous maintenance and updates are:

- CGI/Perl-scripts are used for the assessment and feedback part.
- JAVA-applets are used to interact with Matlab, both for input from the user as well as output from calculations and for generating interactive graphics.
- Matlab scripts are used to deal with simulation, control and identification tasks.
- C++ programs are used to represent certain blocks for speedy operation of Matlab simulations and for piping data from hardware to Matlab or Excell.
- HTML style sheets for the general presentation.
- Excell as a data base for storage of raw data.
- HTML files containing general information.
- www server software Xitami, to control www access.
- DAQview or API-C software for data exchange with the hardware.

In Melbourne, the Electrical and Electronic Engineering Department host a team of 3 IT people that assists with the development and continuous maintenance of its www based course-ware. In house standards and solution methods are being developed to facilitate long term maintenance and continuous improvements.

In conclusion, the typical goals in introductory control experiments are modest, and can be delivered through a virtual laboratory set up. However, it is not all clear that a complete learning experience as for example advocated in [10] can at the present be cost-effectively achieved through means of a virtual laboratory.

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