A PROCESS ENGINEERING VIRTUAL TEACHING ENVIRONMENT

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Abstract *- Process Control is acknowledged to be the technology that has the greatest potential for improving competitiveness in the process industries. Although Chemical/Process Engineers are the natural personnel to carry out Process Control functions, as undergraduates, they often view Process Control to be a subject full of abstract concepts with high mathematical content and hence difficult; and that Process Control is non-mainstream Chemical Engineering. Many are therefore put off by Process Control at an early stage. Laboratories are traditionally used to mitigate this situation, and more recently, computer delivered interactive content have also been reported to be an useful tool in Process Control education. However, both have, up to now, been used as separate teaching tools. This paper proposes a framework whereby the two approaches can be integrated into a Process Engineering virtual teaching environment. Technical and implementation issues are also discussed.*

Index terms - Process Control; Process Engineering; virtual laboratory; CBT.

INTRODUCTION

As reflected in numerous DTI, EC and funding councils' initiatives, Process Control has been identified as the technology that has the greatest potential to improve competitiveness in the process industries. Successful implementation of Process Control methods depends on a fundamental understanding of the characteristics of the controlled process. Thus, Chemical Engineers are ideal candidates for training as Process Control Engineers. Chemical Engineering students, though, often view Process Control as a difficult subject due to relatively abstract concepts and high mathematical content. A significant proportion of students will try to avoid them if Process Control modules are offered as electives.

There are a number of approaches to increase student interest and improve understanding, including:

- Process Control laboratories
- Computer-based teaching systems

It is well known that laboratory sessions are one of the most effective ways of helping students come to grips with abstract concepts. This is vital in Process Control [1]. However, suitable laboratories to support Process Control teaching and learning do not come cheap. There is now an increasing trend to replace traditional laboratories with computer based simulations.

Computer-based teaching (CBT) technology has been around for some time now and computer delivered teaching material in Chemical Engineering has been developed since the mid-1980s [2]. CBT systems present textual, graphical, video and audio content, but those that include simulations are rare. Improved learning or assimilation of knowledge is generally attributed to users interacting with the content, ensuring that they are playing an active role in the learning process. Content developed for delivery over the WWW is platform independent and, together with increasingly cheap computing power, mean that web-based educational material is now readily available to all, facilitating self-directed and distance learning [3]-[5].

This paper discusses the relative merits of laboratories and interactive CBT modules and proposes a blueprint for a computer based process operation and control training system of the future. Design and implementation issues are also discussed.

PROCESS CONTROL LABORATORIES

Suitably designed Process Control laboratories, centred on pilot scale process units, can improve significantly the understanding of key concepts. Students work with real devices such as measurement systems, actuators and pumps and other process and control equipment. The hands-on experience enables them to better visualise process control objectives, and imparts in them, a feel for achievable performances and the problems that can occur. There are limitations though. Fully controlled pilot scaled processes of reasonable sizes require costly floor space, are expensive to buy, run and maintain. Additionally, safety considerations dictate the type of chemicals or material that can be handled. Unlike most mechanical or electrical/electronic systems, process units are usually large scale, continuous and inter-connected. Typical process characteristics such as long residence times, time-varying and non-linear dynamics are not easily reproduced in small-scale process equipment. On the other hand, the dynamics of larger scale units would lead

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to laboratory sessions lasting longer than the typical 3 or even 6 hours. In some cases, steam and air supplies are needed but, in an academic setting, may only be available during office hours. Finally, due to class sizes and equipment availability, not all students may get to participate in the process control laboratory.

Much of the limitations of a so-called 'wet' laboratory can be overcome by 'virtual' (computer-based) experiments. Here, a simulation of a process is run transparently in the background, and students interact with the simulation via graphical user interfaces, to change process parameters, controller settings, etc. Simulator outputs are usually plots and displayed values of manipulations and process responses. Compared to pilot scale laboratories, virtual laboratories are relatively cheap to operate and maintain. There are no constraints with regard to the type of chemicals being handled; the costs associated with material and energy usage and the length of an experimental run. With the virtual laboratory environment, it is also easy to expose students to the control and operation of different processes, and quite complex scenarios. Simulator systems are used widely in the nuclear industries, the armed forces and aerospace industries and their benefits are widely documented [6].

We have used both wet and virtual laboratories in the teaching of Process Control, from undergraduate programmes to post-experience courses. The following are typical favourable feedback from users:

By engaging in Process Control laboratories, students

- have the opportunity to put theory to practise
- are able to better visualise the effects of various control modes and settings

Additionally, with a simulator based laboratory

- students can work at their own pace and experiments are not constrained by laboratory opening and closing times; and by availability of utilities
- mistakes can be easily rectified with virtually zero turn-around time
- problems with equipment malfunction are non-existent

Since the introduction of the simulator based laboratory, we have noticed that the average marks in the final year undergraduate Process Control module have improved significantly. However, the simulator package we use has some shortcomings:

- learning how to work the simulation system may take some time because there is no on-line help
- it is not network aware
- a demonstrator/instructor (more if the class is large) has to be present to re-iterate some of the theoretical aspects which have to be applied (that is the system is not really amenable to independent self- and distance-learning)
- the problem is a ‘closed’ one and is not ‘individualised’
- there is a fixed set of ‘optimal’ controller parameters and process settings. Once these are established, the challenge of achieving the objective is lost.
- it does not promote creative thinking nor engender fully, problem solving skills
- the relationships between Chemical Engineering principles and plant operation to Process Control are not explicit
- the nature and effects of interactions between process units are not included

Most simulator systems suffer from these problems. However, given the current technology, it should be possible to overcome most, if not all, of them.

INTERACTIVE CBT MODULES

Ever since the introduction of computers into educational institutions, they have been used to as educational aids: performing simulations as mentioned above; presenting factual material and aiding student assessment are some examples. Early, pure textual content systems with primitive formatting have evolved to multimedia 'titles' that feature typeset quality text, with embedded graphics, sound, animations and even video. Hyperlinks are used to connect different sections of a title, as well as separate titles. Users are therefore able to explore content non-linearly and usually in increasing detail. More sophisticated offerings are driven by scripts or macros, elevating multimedia titles from mere content delivery systems to applications status. The effectiveness of CBT systems depends on a number of factors, including

- content
- level of interaction
- portability and accessibility

The content must, obviously, be appropriate. Just as important, content must be displayed in a suitable manner, since reading off a screen is different from reading a book, and teaching and tutoring requires different presentation styles. They must offer more than the print versions and, from a pedagogical point of view, the pathways for users interaction must be well designed. The navigation interface, how content is linked and the type of linked content are all influential, [7]-[10]. With regard to portability and accessibility, advances in web-technology and the provision of free 'reader' applications have helped solve platform dependence problems.

A significant recent development is the availability of authoring tools for generating CBT modules (e.g. Toolbook, Director, and Authorware). These enable content providers to put together a CBT module quickly without having to be programming experts. Developing a CBT module may simply involve dragging and dropping 'objects', from a library of components, to set up navigation functions; effect page transitions and so on. Some products even have the ability to generate quizzes for on-line assessments. Despite the progress, authoring systems still suffer from a major deficiency; it is difficult to incorporate simulations, which as discussed previously, can promote understanding of Process Control fundamentals. This is because a suitable programming or scripting language is not built into the system; there is no charting component; or both.

THE NEXT GENERATION

Currently there are virtual laboratories and CBT systems targeted at Process Control [2], [4]-[5] but they are rarely integrated. It would be good if virtual laboratory environments could be supported by an interactive CBT system, and vice versa. It would be even better if there is a development environment that facilitates the production of:

- CBT modules
- simulations and their associated user interfaces
- student assessment and progress monitoring components

and to compile them into an integrated, platform independent, run-time application that conforms to the general information structure shown in Figure 1 below.

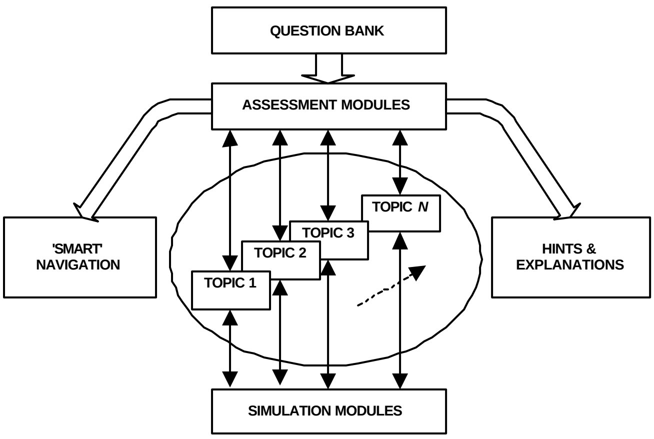

FIGURE. 1
INFORMATION STRUCTURE OF PROPOSED INTEGRATED CBT SYSTEM

To place things within a tangible context, consider a basic Process Control curriculum. The topics below are drawn from the BEng. Chemical and Process Engineering programme at Newcastle, but should be typical of most undergraduate Chemical Engineering courses:

1) **process dynamics**, which include process modelling; solution of ordinary differential equations; linearisation; response characteristics; elementary system identification; Laplace Transforms and block-diagram algebra.
2) **fundamentals of feedback control** which introduce the concept of feedback; three-term controllers; controller tuning and stability analysis.
3) **basic strategies** such as feedforward, cascade and ratio control strategies
4) **advanced strategies** such as dead-time compensation; model-based three-term controller design; interaction analysis and decoupling control; inferential control.
5) **control of unit operations** which would cover typical strategies used in the control of common chemical process units such as heat exchangers, reactors, separation columns
6) **instrumentation and measurement systems** covering basic temperature, pressure and flow measurements; valves and actuators; process signals and their conversion.

These topic categories illustrate the different types of information and knowledge that have to be passed on to students. They also highlight areas where laboratories would be useful. For example, new *terminology* will be introduced in topics (1) to (4) and (6); topics (1) to (5) will involve new *concepts* and *mathematical* manipulations; topic (6) will also contain much *facts* and topics (1) to (5) should be supported by *simulations*. Item (5), in particular, should be supported by process engineering information relevant to each of the unit process being considered.

Organisation of Content

Content organisation is central to the proposed CBT system. The system should support layered access to information so that users can move from simple concepts through to more advanced topics, and from advanced material back to fundamentals, thereby catering to all learning levels and abilities. For example, a decoupling network (advanced) can be viewed as a special application of feedforward control (basic) and simple inferential control schemes (advanced) may be realised with cascade strategies (basic). By establishing such threads between various topics with different levels of perceived difficulty, students can be led from one level to another. This enhances the utility of the system, as it becomes both a learning aid and a reference resource.

Many students view Process Control as a subject separate from mainstream Chemical and Process Engineering. This may be because many Process Control lecturers are from other disciplines, and tend to use examples alien to Chemical Engineering students This perpetuates the misconception that Process Control is not really important, and hence not worthy of study effort. Process Control must therefore not be taught in isolation to other Process

Engineering subjects. Supporting material on how process design affects control performances should therefore be included, especially in topics (4) and (5).

Content organisation is also not a matter of simply separating the material into distinct sections and then presenting them as in an electronic version of a book. How different topics are linked together is very important to the learning process as it exposes the relationships between them and can aid understanding and knowledge assimilation [11]. Concept maps, which are a kind of semantic network, should be used to help organise, integrate and index the content. The structure of the map will also help define navigation pathways [12].

Catering to Different Learning Styles

No two persons learn, study or assimilate information in the same manner or at the same rate. Students from different backgrounds and experience also tend to attach different emphasis to different material. The system should be designed to take into account different learning styles as well. Our experience has been that most students are of the 'Extraversion-Sensing' (ES) type, as classified by the widely used Myers-Briggs-Type-Indicator (MBTI). The ES person prefers structured and experiential learning. Studies have indeed shown that this is becoming the dominant group in modern populations [13]. Therefore, topic navigation will first be directed. As the user begins to master basic material, navigational restrictions will be lifted gradually to encourage freer exploration of more advanced material that may be more conceptual and abstract. Thus, there will be gradual accommodation of 'Introversive-iNtuitive' (IN) learner types, which lie at the other end of the MBTI typology. This suggests that the system should have the ability to assess and monitor progress.

Assessment and Progress Monitoring

In a traditional class setting, on-the-spot assessment of student comprehension and progress is typically obtained by observing students' reactions and by posing questions. Lecture speed, style, emphasis, and perhaps content, are then modified accordingly. CBT systems do not have the ability to enjoy such spontaneous feedback. Still, some degree of progress monitoring could be achieved by including self-assessment components based on the use of 'multiple-choice', 'free-response', 'point-to-area' and 'pick-from-list' questions, e.g. [14]. To prevent students from remembering answers through repeated use, and hence suffer from delusions of achievement, assessment questions should be picked at random from a large source - the 'Question Bank' in Figure 1. Each question should have 'Hint-and-Explanation' facilities associated with each question, to encourage attempts. We also propose categorising each question according to type, e.g. either as 'terminology', 'facts', 'concept' or 'mathematical', and assigned a measure of its level of difficulty.

Assessment sets should appear automatically at the end of each topic but students should also be able to call up an assessment at any point. Upon completion of each assessment, the scores could be used to advise students of their progress and suggest the next course of action. The results of students' efforts should be logged to maintain an individualised progress record. The system should also be able to use assessment scores to re-present information and further assessment material in a transparent, controlled and relevant manner. Students having difficulties would be then helped along gently whilst more able students could be challenged. The manner in which navigational restrictions are lifted could also depend on test results.

Simulations

As discussed already, dynamic simulations are vital to the effective learning of Process Control and must therefore form a major component of the proposed system. We do not advocate the provision of tools that allow users to build and test models and control configurations. This flexibility could increase significantly the learning curve and hence detrimental. Instead, the simulations should serve as training and practise platforms; interaction will be limited to changing parameters of process, controllers and control strategies - much as in a wet laboratory or control room.

For topics that have simulations associated with them, the associations should be two-way to support bi-directional access. Suppose a student encounters difficulties when trying to solve one of the simulation problems. The simulator should be able to detect this and proceed to offer advice or redirect the student to appropriate topics for further study. For example, after 3 failed attempts at tuning a PID controller to ensure that a closed-loop response is well damped, the system could advise the student to reduce the proportional gain, or suggest a review of the topic on controller tuning. This is analogous to the context-sensitive help systems found in most modern computer packages.

There should be two categories of simulations. Linear black-box models could be used to illustrate concepts and aid visualisation, while mechanistic models of units common to the process industries (e.g. heat exchangers, reactors, distillation columns, etc.) should be used to impart some realism, especially for topic (5) above. While realism is important, the emphasis should be on emulating typical dynamic behaviour of such units instead of high-fidelity simulations. This would simplify system development.

DESIGN AND IMPLEMENTATION

The first thing to note is that the usefulness of the system depends ultimately on the content, how it is written and presented. There are many guidelines for producing hypermedia courseware, and these should be followed [7]-[8]. Are there other design and implementation issues? Can the proposed virtual teaching environment be realised easily using current technology?

To ensure platform compatibility and wide availability, the system will be accessed using a web browser. Excluding the simulation modules for the time being, this means that content can be prepared as either HTML or PDF files, these being the tow most popular web document formats. HTML (hypertext markup language) files are text files containing tags that determines how the content will be rendered when viewed using a web browser. They can be edited using any text editor, but it is better to use one of the vast numbers of authoring tools that are available now. Although it's forte is the ease at which documents can be linked together, generating PDF (portable document format) documents is easier; PDF documents can be protected; and a survey of students at Newcastle revealed that they preferred the 'printability' of this file type. However, HTML documents offer more in the their ability to include rich media components such as video and animations via Macromedia's Shockwave Flash File (SWF) format [15]. Nevertheless, it would certainly be worth considering preparing 2 sets of the same document, one for screen display using HTML and a PDF one for printing. There are tools to facilitate such tasks, e.g. eCorporation Ltd.'s RoboHelp application [16].

Another significant advantage that HTML documents has over PDF is that they can exchange information with server-side programs in a more transparent manner. This capability will be required to implement the 'Smart Navigation', 'Hints and Explanations', 'Question Bank' and 'Assessment Modules' components of the proposed system. These parts of the system will require programming. At this stage, we do not know the complexity of the task. The decision-making that occurs within these components suggests the use of artificial intelligence techniques. Then again, it could turn out that simple *IF-THEN-ELSE* constructs might be sufficient, in which case the programming task could be trivial.

The simulations will also need programming. There are 2 ways to do deliver simulations via a web browser: using Java applets, which will require substantial skill with the Java programming language, or through communication with a server-side program. The latter approach is much more attractive given that a MATLAB web server is now available [17]. The MATLAB server intercepts MATLAB commands contained in HTML pages, processes them and returns the results (including graphics) into template HTML forms which are then shown on the user's web browser. This is very convenient, as MATLAB has arguably become the standard programming environment for Process Control systems analysis, and most Process Control lecturers should know how to program in MATLAB. However, the graphics returned by this implementation are static. If animated plots are required, then Java applets have to be used, with its attendant learning curve.

Finally, it is clear that the overall system design should be modular to facilitate reuse of topic components; accommodate contributions by different domain experts and addition of further material. A modular design will also enable changes in content (brought about by course restructuring, new requirements or changes in emphasis) to be made in a manageable and incremental manner.

CONCLUDING REMARKS

This paper has so far provided a functional specification for an education environment that combines traditional CBT and virtual laboratory components. The built-in intelligent interactive elements should enable the system to accommodate a range of entry levels as dictated by the experience and requirements of users. The framework should be applicable to any lab-based subject or subjects where learning will be aided and enhanced by visualisation and hands on exercises. The system can be realised with current technology but several tools have to be used to generate the core components. Integrating these seamlessly could prove to be a challenge.

If successful, the system could have an immediate impact on remedial teaching, continuing education, distance-learning and technology transfer in general. Further, the proposed system can be developed into the one shown in Figure 2 at the end of the paper. Here the environment has been expanded to incorporate the following main components:

- **Simulator**: This contains 4 sub-components, the main one being some process model drawn from a library. The others are used to simulate conditions that can happen in practice, e.g. changing throughputs, stream compositions, ambient conditions and equipment failures. With the appropriate external interfaces, a real process can replace the Simulator component.
- **Tools**: This component contains a series of sub-components; applications which will enable users to make calculations; maintain notes; and perform analyses.
- **Knowledge Base**: The 'On-line Help' contains instructions on how to use system while the 'Scenario Description' describes the simulated system. The others are designed to help users recall and apply domain knowledge. The 'Process Control' component is as described above. The 'Unit Process Principles' component provides fundamental information about the design and operation of the process being simulated;

the HAZOP/HAZAN component contains data about the possible hazards and faults that can occur during the operation of the simulated unit. The 'FAQs' component contains answers to frequently asked questions.

- **User Interface**: This is only visible part of the system. Output from the 'Simulator' will be shown on the 'Operator Console', which will be presented along the lines of typical Distributed Control Systems displays. Users can switch between display formats: a mimic diagram or response plots. There is also be an 'Alarms' display that activates when key process variables exceed prescribed safety limits. Users adjust parameters via the 'Control Panel' and changes are logged for diagnosis and feedback. A 'Workbench' is included as part of the user interface to allow users to call up material from the 'Knowledge Base' and to perform analyses using the applications provided by the 'Tools' component.

In this expanded system, the relationships between the various areas of Chemical and Process Engineering are made more explicit, and the content is more integrated. It is therefore more self-contained and is closer to an ideal Process Engineering virtual teaching environment.

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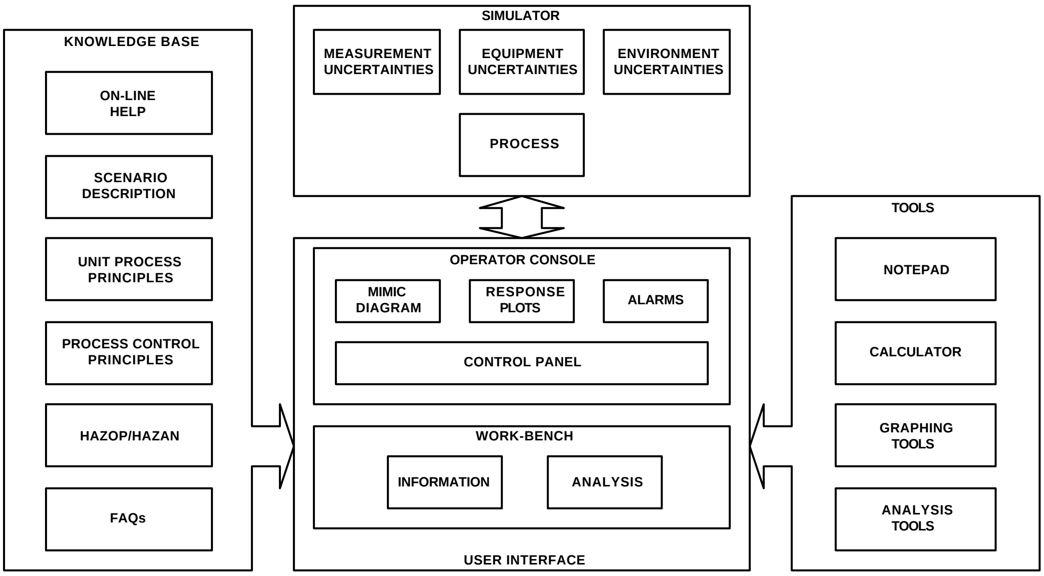

FIGURE. 2

SCHEMATIC OF A PROCESS ENGINEERING VIRTUAL TEACHING AND TRAINING SYSTEM