ENGINEERING EDUCATION USING DISCOVERY II

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ABSTRACT

Engineering can be considered to be the application of scientific knowledge. It is a field where 'hands-on' knowledge of equipment is very often considered essential. Feedback Instruments designs, develops, and manufactures engineering training systems that are used within universities and technical training centres. Some of these systems are supported using a web-based training system that presents scientific theory alongside instructive interactive practicals, allowing students to take control of real systems to explore the principles behind hardware that may be found in the real-world. Three training packages used within the Discovery II web-based environment are presented, a basic-electricity and electronics trainer, a telecommunication principles trainer and a series of process control trainers.

1. INTRODUCTION

Feedback Instruments primarily manufactures hardware systems - instruments or devices - that allow students to understand how they work, allowing them to grasp underlying principles and theories. The intention of the hardware is to make the 'invisible' theory to become immediately 'visible', thus understandable. With many of the hardware training systems, software plays a very important role in helping the student to understand phenomena that can often be difficult to grasp by allowing the behavior of a system to be visualised.

The following section describes one of Feedback's most important products, entitled *Discovery*. A brief historical outline is presented, followed by an outline of the software technologies that it currently employs. *Discovery* can be used for engineering education within several fields. Feedback's portfolio of training systems ranges from basic electricity and electronics, fundamentals of computing, analogue and digital telecommunication principles to industrial process control and servo systems.

2. DISCOVERY

The philosophy behind *Discovery* lies with the idea that explanatory content, describing how a real system can be modeled and operated could be placed alongside real physical hardware that could be used to demonstrate and complement the theory. Central to *Discovery* lies the concept of the 'practical'. A practical is an experiment that a student can perform with real hardware. Within *Discovery*, many practicals utilise 'virtual instrumentation'. In many cases, a *Discovery* practical directly interfaces, using various devices, to the hardware that the student has been asked to control. Students could begin by reading about the mathematical theory

behind amplitude modulation, reading some background information describing its uses then, and then begin a practical where physical hardware is then controlled, allowing an amplitude modulated signal to be examined, studied and questions answered.

Discovery products are divided into separate 'assignments'. An assignment is a group of 'practicals' which is used as a starting point for the exploration into a certain concept or idea. An assignment can contain a number of related 'theory pages'. Associated to a practical could be a number of background pages, a patching diagram and finally a set of related questions.

A 'patching diagram' is an interactive diagram that demonstrates how hardware needs to be configured before it can be used for a certain practical. Hardware systems can be made up of many different configurable units, each of which are connected together by a student or a lecturer. Patching diagrams are most commonly used within a series of training products relating to basic electricity and electronics – packages of products that demonstrate the use of electrical components, such as diodes, capacitors and resistors, and induce students to the essential laws of electricity. Students are asked to follow a patching diagram, placing components on a breadboard. It later illustrates how instruments are to be connected to the circuit, prompting the students to take measurements and draw conclusions about a circuits behavior. Patching diagrams are also used with the industrial process trainer software, Procon, which will be described later. Here, a controller must be connected to a range of separate and essential devices, such as sensors, valves and motors.

When patching has been completed, the student is then asked to begin a practical. On the screen, an instrument or a representation of the physical hardware may appear. Students are asked, through the practical, to make adjustments to controls, changing voltages or pressures and to take measurements at regular intervals, and then answer questions corresponding to what they have just observed. From the original theory, through to the configuration of components, to the observation of understandable behavior, all are integrated.

The original version of *Discovery* was DOS based. A part of its original development consisted of a simple 'content browser', that allowed textual information to be presented alongside simple graphics. To facilitate the movement throughout explanatory text, a very simple 'mark-up' language was devised. When it became evident that redevelopment was needed, the selection of web-based technology seemed to be the most prudent route to adopt. One large problem remained – namely how to integrate low-level hardware communication within a browser-based environment. The Java language provided the answer not only to one problem, but also to several other problems. While low-level communication to custom designed hardware has proved challenging, the use of Java has to potential to make any software that has been developed work on more than one computing platform. The following sections describe interactive *Discovery* software that all utilise the Java platform.

2.1   ELECTRICITY AND COMPUTING FUNDAMENTALS

The basic electricity and electronics trainer consists of an A4 sized breadboard that can be placed easily into a students power console. Using the breadboard, students can build-up a variety of electrical circuits using a set of available components, apply power from the console and take measurements using standard test and measurement equipment. Originally, the trainer was provided with a standard paper-based manual, comprising of a range of circuit configurations and practicals. The manuals were provided with 'patching diagrams' that illustrated how the components should appear on the breadboard.

A computer-based equivalent was developed, enabling a computer to direct a students study of electrical theory. The basic electricity and electronics training software begins with a study of DC circuit theory, comprising of resistance in series and parallel, the concept and

measurement of power and the introduction of capacitance and inductance. An AC section goes on to describe and present AC power, resonance and transformers. The final section then moves on to semi-conductor devices, such as the diode and the transistor. This 'basic' series of assignments and practicals is then complemented with trainers entitled 'amplifiers and circuit applications' and 'operational amplifier tutor'.

The *Discovery* software takes the student from the initial theoretical content, to descriptive background information, which may include a discussion relating to materials of which components are made of, to a practical. Following the use of a patching diagram, the student will then occasionally be asked to fill out printable 'measurement' forms.

There are a number of computer-based training packages of this form. The *electromagetics trainer* consists of discrete groups of components that can be connected together to form different circuits. This covers topics such as magnetic materials, motor and transformer design, and electrical generation. There are further boards of this kind; a logic tutor demonstrates the fundamentals of logic circuits, a digital systems board is used to show the fundamentals of modern computing, and an analogue board is illustrate the difference between analogue and digital systems and how they can be used together.

Figure 1 : Digital Systems Patching Diagram

Figure 1 illustrates a patching diagram used on the 'Digital Systems' training board that is used to study parts of the fetch-execute cycle used within all microprocessors. In this patching diagram, the student is shown how to configure the board, where one of the registers can be used as a 'program counter'. The grey areas indicate parts of the board that are not utilised for this practical.

The browser-based basic electricity and electronic trainers are 'software only' in the sense that they guide the student through circuit configuration. The software is not used to take measurements or control the hardware. Operation and configuration is left in the hands of the student. The software is provided as *support* to the original hardware. The electronics and basic computing trainers can be used without *Discovery*. The software represents a translation of a paper-based manual into an attractive, colourful, modern, interactive format. The two hardware products that follow can in no way function without software.

2.2 TELECOMMUNICATIONS

The Telecommunication range of trainers is one of the most comprehensive and sophisticated systems developed. Two telecommunication principles trainers are available – one for analogue communication, another for digital communication. The analogue trainer examines amplitude modulation, frequency modulation, studies how signals can be generated and studies the operation of simple filters. The digital trainer studies the encoding of symbols into a 'digital representation', such as ASCII or morse code. This is followed by how digital signals can be transmitted, using techniques such as Amplitude Shift Keying (ASK) and Phase Shift Keying (PSK) and how noise on a digital link may affect transmission effectiveness. Finally, the basics of fibre-optic communication is covered.
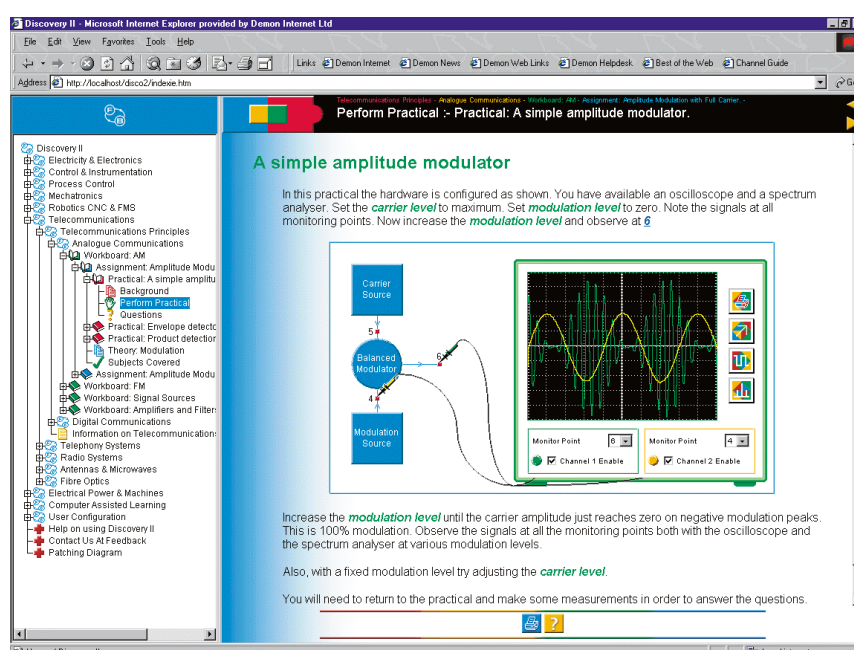

Figure 2: Virtual Oscilloscope connected to an Amplitude Modulator Circuit

The telecommunication principles trainer consists of several A4 sized boards that are plugged into a device named a Rapid Access Terminal, or RAT, for short. The RAT is a high-speed analogue to digital converter with additional control lines that allow the telecommunication boards to be configured and controlled. When a practical page has been loaded, an instrument is displayed on the right, and an oscilloscope probe on the left. This probe can be dragged to using the mouse to different 'monitoring points'. Real equivalents of the monitoring points can be found on the board where a real oscilloscope can be attached, producing the same results as displayed within the browser window. Various instruments can be used to obtain an understanding of the behavior of the circuits. As well as an oscilloscope, illustrated in Figure 2, a spectrum analyser and in some instances a basic plotter used to display signal strength against frequency is used. Like a modern digital oscilloscope, markers can be moved around the display allowing precise measurements can be taken, even down to the level of a nanosecond. Other smaller instruments include a voltmeter and a basic frequency meter.

Each board can comprise of a number of switches and potentiometers to change how the circuit operates. The 'Tuned Circuit and Filters' contains a battery of different controls and switches. Circuits can be tuned, measurements can be taken, and capacitors can be changed by

the flick of a switch to demonstrate difference in circuit behavior. The effect of on-board 'real' controls is most visible within the 'picture transmission' practical. Here, a simple graphic is transmitted to one of the digital trainer boards, where noise can be introduced to the transmission, where it is transmitted back to the computer for display. The digital transmission of noise appears remarkably resilient until a certain threshold is reached, where it suddenly breaks down.

Further training systems of this kind are currently being developed. Telephony is the study of telephone systems, their standards, their technology and how they operate. Two groups of telephony trainers have been developed. The first introduces the different types of signals that common telephones use, such as 'tone dialing' and addresses important topics such as analogue to digital conversion and multiplexing. The second trainer is a dedicated microprocessor controlled 'digital switching system' that aims to mimic actions found on a real-world telephone digital switching centre or exchange. Small banks of telephones can be connected together via an additional 'trunk' board. Students are encouraged to call other students. Changes in the state of the exchange are represented on the display of the computer. While telephony cannot immediately be considered to be a science, these trainers directly address issues such as frequency, spectrum analysis, noise and other issues that are directly relevant to telephone systems, such a crosstalk and attenuation.

2.3 PROCESS CONTROL

The discipline of process control is the study of theory, systems and technology used to control physical systems. The application of process control technology is wide ranging. Its study can be applied to the control of systems within manufacturing plants and large industries, such as power or chemical plants to the fine control of critical transport systems, such as the maintenance of a constant speed of an electric motor on a train. Two different types of process control trainers exist within *Discovery*; the Procon range and a servo system, entitled Digital Servo Fundamentals.

2.3.1 *Procon Process Control Trainers*

The *Procon* range of trainers comprise of four desktop rigs that each have a set of unique properties. The level and flow rig allows the study of the principles of control using liquid level and flow rates as process variables. This rig can be connected to a temperature rig that allows a more complicated 'dual-loop' system to be constructed. The temperature rig allows the mechanisms that allows temperatures to be maintained at a set constant, useful in instances where a constant chemical reaction has to be maintained. This rig also demonstrates cooling, where a simple fan and radiator are used.

One of the disadvantages of the temperature rig lies in that it has a very long 'cycle-time'. It can take tens of minutes for a temperature to reach a specific 'set-point'. This rig, however, can be complemented by a 'pressure' trainer. Instead of using water as a process fluid, it uses air, demonstrating how pneumatic systems can be controlled. The 'cycle time' of this rig is considerably shorter, some experiments taking seconds to 'cycle' rather than minutes. The final rig in the series is the pH trainer. This final rig allows two chemicals to be mixed, a chemical reaction to take place, creating an output liquid. The purpose of this rig is to demonstrate the need for toxic chemicals to be treated with other chemicals to ensure that they are not dangerous to the environment. After the two chemicals are combined, the output solution is a non-toxic salt solution. Discussions relating to the basics of chemistry make up a portion of the theoretical content. This rig demonstrates principles of 'environmental engineering' and shows that pH as a process variable can be very difficult to control.

Each rig has been built using a collection of industry standard actuators and sensors. These are connected to a 'process interface' which are then, in turn, connected to an industry standard process controller. It is the controller that controls the rig, but it is the *Discovery* software that configures the controller and allows the student to easily manipulate its operating parameters, displaying the results of the process using a simple chart recorder.

Practicals begin by studying the components of the rig, addressing issues such as calibration, then moving onto the examination of different process approaches which have been described within the theory section. Students are instructed to alter on-screen parameters to change heat or liquid levels, or introduce or remove process stability.

2.3.2 Servo Fundamentals

The Servo Fundamentals Trainers demonstrate similar 'control principles' to the *Procon* trainers, but using different technology. Instead of controlling a large industrial-like process, a simple stepper motor is used.

There are two components to the unit - a mechanical unit and a digital unit. The mechanical unit is a small desktop system that can be placed easily next to your computer. Like the *Procon* systems, it consists of a number of sensors. It comprises of an input potentiometer on the front of the unit that can be used to control the motor, a potentiometer used to detect the behaviour of the motor, a tachogenerator and a digital encoder. Each of these input devices have their own particular set of characteristics. A load, or 'brake' can be placed on the motor to simulate 'resistance' and differences in system performance observed between two types of motor drive types - dc voltage only, or pulse width modulation motor drive, the type of motor drive often used on underground or subway trains.

The digital unit provides an interface to a computer. It also allows the motor to be optionally driven by a group of circuits that generate types of 'waves', where a 'triangle wave' or a 'square wave' can be generated and adjusted using a frequency and 'signal height' control. Alternatively, the computer can generate the control signals and read the state of the systems various sensors. Using the training software, the student can gain an understanding of proportional, derivative and integral control, and how these types of control can be best applied to respond to certain types of input signals.

The digital board can be configured in a number of different ways depending upon how components on the board are set up. Clearly visible on the silk-screen printed circuit board are the systems analogue to digital converters, inputs from the tachogenerators and the direction of data communication to and from the PC. An analogue only board is also available to complement the digital system. No computer interfacing is provided and process control is studied in analogue form only

3. COMPUTER DRIVEN DISCOVERY

The *Procon* and the Digital Servo systems integrate patching diagrams, descriptive text and graphics, with a simple chart recorder and process controls. By configuring the hardware devices manually, and understanding of the component parts can be understood. By connecting them to the interface systems while running a process, their effect on a dynamic process can be appreciated. It is a combination of the on-screen controls and the chart recorder that makes the invisible become visible.

The software's power lies in its ability to present immediate 'feedback'. A student can immediately see how a system may operate when one or more parameters are changed. Figure 3, taken from the Digital Servo system illustrates two simultaneous 'traces'. One trace indicates the 'actual' position of the servo mechanism, the other indicates the 'required'

position of the servo mechanism. Different control parameters change how close the 'actual' signal may get to the 'required' signal. Dramatic shifts in the signal will necessitate the application of different control variables.

Figure 3 : Digital Servo Fundamentals Trainer – Chart Recorder

Theoretically, simulations could allow a student to create possibly dangerous situations within processes without having to pay great attention to any resulting consequences. Simulations also never wear out and they never need to be left so that they can 'cool down' after a set of experiments. A simulation, however, can never take the place of real hardware, since it is ultimately 'real' hardware that engineers have to repair, maintain and examine. Real hardware is imperfect in the way that perfect simulation systems are not. Each component has its own unique properties. Real systems are made of cable, screws and electrical components that can age and wear out with time. While numbers can be used to represent water, heat or movement, they are ultimately nothing more than a representation. Simulations do not make the 'noise' of the real world and they do not have the 'feel' of real components found in the field, but they do not 'break' like systems in the real-world, either – their performance does not degrade and they are not prone to catastrophe.
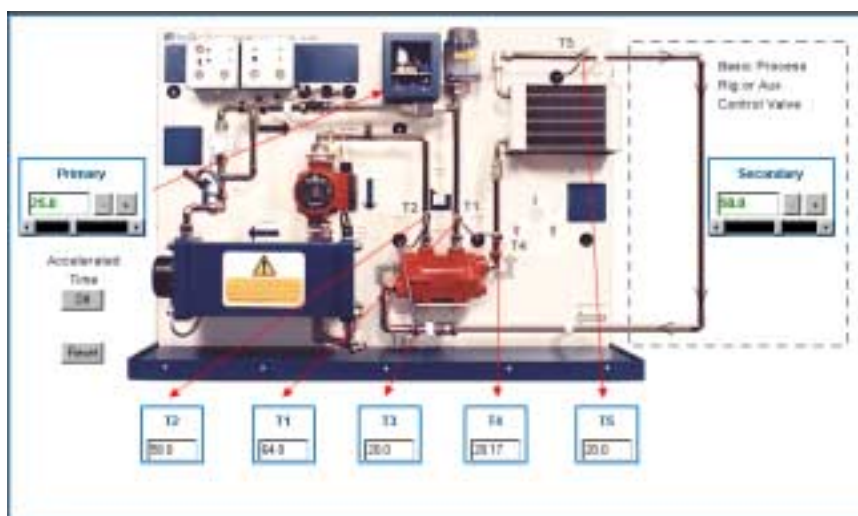

Figure 4 : Simulation of the *Procon* Temperature Process Rig

Simulation systems are now an important part of the contemporary engineers' toolkit. They possess the ability to 'try things out' before expending significant time and expense on a real system. *Discovery* incorporates several simulations (see figure 4). For the Digital Servo system, a mathematical model of the entire system is provided in the form of a Java applet. This allows the student to appreciate how a simulation relates to the behavior of a real system. Like with the real system, instability can be introduced. The controlled system can begin to 'overshoot' and 'undershoot' depending upon parameter settings. Similar simulations can also be found within the *Procon* range. Above is an illustration of a simulation used with the temperature trainer. Here, time can be accelerated so the 'process liquid' heats up faster and temperature can be 'reset'. During equivalent real practicals, students can take their calibrated meters to take readings to see if any differences exist between the simulation and the real system.

4. DEVELOPMENT ISSUES

The original version of *Discovery* began development approximately ten years ago. The latest version of *Discovery* has been three years in the making. Dean and Whitlock, [2], state that it takes between 100 to 200 hours to produce a single hour of CBT courseware. The telecommunication principles courseware consists of 97 practicals. If it takes 20 minutes on average per practical, it would take 32 hours to complete the whole course. It is conservatively estimated that over 4000 development hours have been spent in producing the current version of the *Discovery*. This figure includes graphical design work, web infrastructure development, development of content pages and the development of tuition applets, amounting to a ratio of 125:1. This ratio, however, does not take into account any of the curriculum development work. It is assumed that the real ratio is towards the end of the estimated range.

Two different teams have worked together to produce *Discovery*; a team of software engineers and a team of dedicated curriculum developers. This encourages the software developers to concentrate on the architectural and design issues of *Discovery*, while dedicated specialists pay particular attention, given the appropriate technology under study, to the didactic needs of students.

The most difficult part of the software development work is believed to lie with low-level hardware communication. One developer disagreed, stating that it was the interfacing between two different software technologies, namely C++ and Java, that proved to be the most troublesome. Development of the software requires a combination of skills. One facet of the development includes the graphical design and image manipulation work. Graphics are integrated closely with all interactive applets and explanatory content. Development can occur at the level of end-user applets, or at the level of a low-level device driver, even down to the level of the assembly language in some cases. Integration of all levels into a browser and mediating hardware control through a Java virtual machine proved to be a challenge that was possible to overcome.

Development approaches have also evolved since the original version of *Discovery* was utilised. Stronger software development methodologies have been adopted, most significantly, the use of round-trip engineering and the modern use of 'refactoring' [3]. Diagramming languages and tools have also played a part, particular UML [1], which has used to aid communication of software designs between programmers and to document designs. Finally, following the development of the telecommunication trainers, a library of reusable classes have been developed and shared between all programmers to standardise a generic *Discovery* look and feel.

5. FUTURE DIRECTIONS

At its current stage of development, *Discovery* comprises of approximately 850 separate practicals that are illustrated by a total of 400 unique 'patching diagrams'. Despite this impressive size, *Discovery* is a suite of products that are by no means complete.

Discovery is continually evolving. A project is currently underway to develop an integrated 'ultrasound transducer kit', where students can begin to understand the theoretical principles behind ultrasound technology and the applications that it can be put to. Similarly, developments are underway to develop a set of *Discovery* software for a range of power electronics systems. Rather than working in the range of tens of volts as the basic electricity trainers do, electrical engineers have to learn about how to manage and measure devices working at levels of hundreds of volts. The PowerLab system will integrate theory describing laws of electromagnetism and like with *Procon* range, will be complemented by some context specific descriptive background and patching diagrams, culminating in a computer led exploratory practical.

The underlying purpose of *Discovery* software is to support the student. In the practicals for the basic electricity and electronics software, the student is often requested to take a note of measured values at certain intervals and plot a graph to illustrate the effect. There is no reason to prevent the adding of simple graphing and visualisation capabilities to a practical, helping the student to more clearly see patterns that will then lead on to the confirmation of laws. Ultimately, there is the potential that such data capture can be automated, as it is partially within the X-Y plotter facility within the telecommunication systems. In all cases, it is essential to ensure that any additional features and systems do not detract from the ultimate aim of teaching and demonstrating fundamental concepts and ideas.

Future developments of *Discovery* and its associated hardware will be partially be dictated by the changes in PC technology. Another concurrent development is to replace legacy hardware interfaces with newer, more flexible hardware interfaces, such as USB. Similarly developments will be dictated by changes in technology. Circuit switching trainers may have to make way for packet switching trainers. Amplitude modulation trainers may have to make way to Digital Signal Processor trainers. Simulation may become more and more important as the roles of engineers gradually evolve.

The original *Discovery* software was much simpler. Trainers could edit the 'marked' content files and add additional instructions or descriptions with little training. In the new version of *Discovery*, it is not currently possible for a tutor to easily add additional text or questions, further extending the set of assignments and practicals that have been defined. Developments are progressing that will not only allow a tutor to author text, but also to manage and control an entire training laboratory, allowing for the scheduling and monitoring of student usage of particular equipment. Such a development is entitled 'Discovery Manager' will sit at the level of a training laboratory between the students workstation and a campus or institution wide computer assisted learning system. It will provide a way to assess students theoretical knowledge through the administration and management of sets of hardware related questions.

ACKNOWLEDGEMENTS

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