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A Network-Centric Approach to Computer Science Education & Research Based on Robotics

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Running Head: Robotics Based Computer Science Education

Summary

A network-centric university teaching and research environment based around mobile robots is described. It supports teaching a wide spectrum of computer science and engineering subjects (eg digital electronics, computer architecture, operating systems, communications, distributed processing, software engineering, machine vision, artificial intelligence, embedded computer design, real-time computing, HCI, Computer Graphics, Virtual Reality etc) within a single unified experimental environment. This enables students to combine their coursework so as to build more complex, interesting and industrially relevant systems thereby significantly increasing their motivation and knowledge. The laboratory infrastructure makes extensive use of networks to produce a versatile and cost effectiveness teaching and research environment. This paper will focus on the teaching aspects of the laboratory describing the technical infrastructure showing how it is used to support the Essex University information technology curriculum and report on the effectiveness of the approach. Finally, to demonstrate the more general academic synergy provided by this laboratory a short overview of some of the research applications is presented.

1.0 Introduction

In this paper we describe a laboratory based on *network-centric* technology and *mobile robot* applications which seeks to provide an imaginative, stimulating and challenging teaching environment. It facilitates the integration of courseware across the entire computer science curriculum and fosters a creative attitude whilst providing a framework that develops theoretical ability, subject knowledge and practical implementation skills relevant to the needs of industry. The laboratory infrastructure makes extensive use of:

- networks (to integrate physical systems; all the systems including the low-level hardware racks and mobile robots are networked),
- cross-platform programming tools (to provide both development access to naked embedded processors and offer location independence),
- simulators (to emulate digital circuits, software kernels and high-level robotic systems for pre-implementation development work or expensive experiments such as those requiring large numbers of robots)
- tele-distance technology eg tele-presence & tele-conferencing (to allow students to see & control remote robots or to liaise when involved in distance or group work).

Thus, by utilising a connection from any remote network node to the robots, simulation or cross-development software servers, a student situated outside the laboratory may have a virtual presence within it. This greatly increases the potential *accessibility* and *utilisation* of the facilities both for local and distance learning paradigm. The use of network-centric technology and mobile robots combine to make this a highly *motivating* and *cost-effective* teaching environment, substantially more cost effectiveness than the traditional laboratory it replaced.

1.1 The Challenge to Educators

According to many leading industry visionaries computing is entering a fourth wave, "the network-centric age", which is set to revolutionise computing practice [1, 2]. These, and other, developments in computer science bring many challenges to educators. One is to harness these technological advances to the benefit of to education [3, 4, 5, 6]. Another is to sustain students' interest as they wrestle with the often difficult, but necessary, theory underpinning scientific and engineering methodologies. A further challenge is to provide a setting in which students can learn to integrate the ever-advancing, widening and deepening range of specialisms within the subject.

1. 2 Technology Rational

Many influential reports [7] have identified both computer networks and embedded computing systems as being critical catalysts to the future success of western economies. Networks are becoming pervasive finding themselves in environments ranging from houses (eg X10, CEBus, LonWorks), through vehicles (eg CAN) to the broadband national networks (eg SuperJanet). Embedded computers are becoming equally ubiquitous as processors are built into an ever increasing list of goods including washing machines, central heating systems, scientific instruments, automobiles, trains & spacecraft. Data communication is becoming ever cheaper, perhaps asymptotic to zero [3] whilst embedded computers are allowing products to become ever smarter. This twin advance promises to transform the way we live, the nature of the education we need and, most importantly for the focus of this paper, the way that education is delivered.

Perhaps one of the most enduring images of the future painted by science fiction is that of an intelligent humanoid robot [8]. Generations of science and engineering students have been inspired by fictional accounts of worlds inhabited by such intelligent machines. Likewise generations of scientists and engineers have aspired to harness the power of computers to improve the delivery of education [9]. Numerous trials are underway that are evaluating the feasibility of delivering education via new technologies such as broadband networks and multimedia services, most augmenting conventional correspondence course techniques using new technology such as Internet based email and teleconferencing etc [3, 5]. The focus of the work described in this paper complements many of these approaches by providing a network-centric virtual robotics laboratory that can be interactively used by geographically distributed students to conduct traditional computer science based coursework. The use of intelligent embedded computer systems, in the form of mobile robots, together with data communication networks has been found to be a highly motivating and cost effective means of delivering general computer science education to both local and remote sites.

1.3 The Mobile Robot Theme

We have found that a mobile robot theme is ideal for educational purposes. It is highly motivating as it encapsulates the dreams of many aspiring scientists and engineers. It is also satisfying in that even the weakest student can produce a software or hardware module that can be immediately seen to function within a larger system. The robotics theme of the laboratory concentrates on the mobility and navigation of robots rather than traditional engineering aspects such as control theory, kinematics or dynamics of motion. The study of mobile robots involve the whole gamut of computer science techniques including distributed artificial intelligence, machine learning, vision, planning, programming methodology, hardware/software interface, operating systems, data-communications, parallel architecture and chip design. The most able can make a real contribution to a research project. Unlike many other institutions, robots are not used as the primary focus of the teaching but rather as a means to encapsulate some of the practical applications in an interesting and universal assignment framework. Thus, robotics[1] as a field of study takes second place to the underlying educational aspects of Computer Science and the provision of a solid set of teaching tools.

2.0 An Overview of the Laboratory

As can be seen in the following diagram (figure 1), the laboratory is composed of a fleet of mobile robots, host computers (which provide an environment for program and ECAD development) and bench based development hardware in the form of VME systems (known as targets, in cross-development jargon). All machines are connected by conventional ethernet, although the mobile robots, which only require the network for initial program loading or monitoring and debugging, may also use a wireless modem. The laboratory network is connected to the departmental and university network via a managed bridge which acts as a "firewall" to protect the wider network from incompetent or malicious students.

Figure 1- Overview of Laboratory

2.1 Robot Environment

The teaching robots[2] which are the focus of this paper comprise a small wheeled chassis (approx. 1ft cube) containing motors, sensors and an industry standard VME bus based system (3U) onto which can be plugged various computing boards and interfaces. A fully equipped robot costs about £3000 sterling. The bench based development systems also comprise the same VME system but in addition, utilise a box emulating the main robot functions (eg motors, bump switches etc). Using VME racks for the both the robots and the bench development systems enables the provision of a development environment which is wholly consistent (i.e. all hardware and software appears to be identical on the robots and bench racks). The software environment is VxWorks[3] (and more recently Wind River's[3] latest product, Tornado[3]), a highly modular real time operating system, which provides a full range of cross development and debugging tools (described in greater depth fully later in this paper). Thus, by utilising a network connection the full range of debugging tools can be applied to robots, even while they are executing real tasks.

Photo 1 - One of the VME based Robots (Ford) & IR Beacon

[1] Since submitting this paper Essex University has introduced both under- and post- graduate degree schemes in “Robotics & Intelligent Machines” (to commence Oct 1998).
[2] Since submitting this paper we have developed a fleet of desk-top micro-robots.
[3] VxWorks & Tornado are trademarks of Wind River Systems Inc

2.2 Host Environment

The bench based host computers are PCs which can run either Unix (currently Linux) or Windows95. All the development and compilation for the mobile robots and bench based emulators is done on these hosts.

Photo2 - Host & VME Development System

2.3 The Software Environment

The bench systems and mobile robots run a highly modular, commercial, Real Time Operating System called VxWorks (more recently, Tornado). Compilers, high level debuggers, simulators and the like all live on the hosts. The cross-development nature of VxWorks means operating code is placed and debugged on the targets in a manner transparent to the host. The characteristics of the operating system are shown in the following table:

Table 1 - RTOS Characteristics

Many of the tools are extensions to the GNU toolset which were supplied for our Sun & PC environment. We have ported them to Linux, and HP Apollos and have written drivers for the low cost HM[4] VME boards we use. VxWorks (& Tornado) integrates smoothly into university Unix environments which, coupled with its elegant principles, makes it an excellent computer science teaching tool.

2.4 Simulation and Emulation Tools

Even though we are relatively well endowed with hardware, we have found significant advantages in utilising software simulation and hardware emulation tools. For instance they have reduced the amount of hardware required (directly reducing the laboratory setup cost), speeded up the development cycle (allowing students to achieve more in a given time) and given students experience of widely used industrial pre-fabrication design techniques. Simulation is of three types. At the lowest level we utilise conventional ECAD digital circuitry simulation, in our case for Altera EPLDs. For the robot software we use a commercial product, VxSim that simulates a complete VxWorks OS running as a process under UNIX. It is possible to log into a VxSim process, download a program and run it exactly as if it were a real target (i.e. robot) running on its own processor. For high-level simulation of complete

[4] Trademark of HM Computing Ltd

robots and their environments we use an in-house designed package called "Virtual-Robots" (described in the Chernett paper, also in this issue). The idea is to provide a "behavioural" simulator able to test higher-level mobile robot algorithms such as those for route planning and especially algorithms involving multiple, communicating robots. Normally, the code transfers from simulation to VxWorks/Tornado with minimal modification. The user can start any number of robot programs; the simulation provides a two-dimensional graphical view of the experimental space in which various obstacles can be placed. The underlying processor engine for the simulation is fully distributed and can be made to run across any number of networked workstations.

Illustration 1 - Virtual Robots (Ver.1) - Screen Dump

Hardware emulation is provided in the form of cheap bench units containing buttons and a stepper motor to mimic the robot chassis which, in combination with VME based bench racks, substantially reduce the number of real mobile robots required.

Photo 3 - Robot Hardware Emulator

2.5 The Network as a Virtual Laboratory (& distance learning facility)

The ability to replace targets by simulations enables students to conduct work on any machine capable of running them. In addition, the underlying cross-development architecture of the VxWorks/Tornado means that even when real-targets are being used, their physical relationship to the host development system is only an issue if the students need to interact physically with the target hardware in question. Thus, by utilising a network connection to the target hardware or the simulation servers, a student situated outside the laboratory may have a virtual presence in it. This increases the productivity which may be obtained from the facilities by extending access beyond the time limits imposed by usual safety or security considerations associated with hardware laboratories. To enable running robots to be observed remotely, a special network camera server, etherCam[5], and miscellaneous support has been developed. There are a number of projects concerned with control of robotic systems across networks, an excellent example being Netrolab at the University of Reading [19] .

2.6 ECAD Tools

Programmable logic devices and associated electronic computer aided design (ECAD) packages have replaced many of the discrete, component design based methodologies which were commonly used in the construction of previous generations of digital systems. This approach has considerable advantages for education. It reduces the student time needed to implement hardware designs by providing computer assistance with the task of circuit entry, simulation and fabrication, allowing devices to be used in a similar manner to that of conventional processors. It is now quite possible for students to

[5] the etherCam server is available from netCam Ltd (sales@netcam.co.uk)

experiment with a number of variants of a hardware circuit within a single assignment period. The ECAD software used in this laboratory was supplied by the Altera Corporation of San Jose, USA (who invented the first EPLD, the EP300, in 1984) and runs on Sun, HP and MS-DOS platforms. A student coursework assignment using these tools to produce a DRAM controller is described below.

3.0 Supporting Computer Science Curricula

We use the laboratory in three ways. In the first, the mobile robots theme provides an educational thread from basics to a working, integrated robot system. In the second, the power of the facilities is used to augment the teaching of a number of stand-alone courses at different levels. The third use of the laboratory is for project work (3rd year undergraduate, M.Sc & Ph.D postgraduate). The following table summarise some of the activities offered by the laboratory. It can be seen from this list, which is by no means exhaustive, that the field covers the gamut of the computer science repertoire. Indeed, it is typical of the multi-disciplinary nature of most functioning computer systems.

Table 2 - Some Potential Activities

3.1 The Mobile Robot Theme and Contest

Within the theme, staff set individual assignments to suit their courses by selecting an incomplete set of modules and getting their students to develop the missing one. These could be hardware or software based. Wherever possible, we try to create design oriented assignments, which we feel provide higher levels of freedom and motivation than procedural based alternatives. As a climax to the year, a competition (for a small prize) is organised which allows the students to combine separate assignments to build a fully working mobile robot able to solve some problem. This approach not only adds to the interest and motivation but offers the educational benefits of providing a mechanism for supporting teamwork and larger projects. The mobile robot theme clearly draws on the research domain whilst simultaneously offering students immediately applicable industrial skills. There is thus great potential for integrating mobile robots into computer science.

3.2 Assignment Support for Specific IT Courses

The following are not exhaustive descriptions but rather give an indication of the type of issues addressed.

3.2.1 Hardware Design

The methods and equations used to design hardware are strongly dependent on understanding the underlying natural phenomena (unlike with software) and our ability to identify and analyse the numerous variables involved. Current limitations mean hardware models are frequently based on assumptions and simplification which students sometimes misinterpret as complete truths. Thus, they frequently find themselves bewildered by the failure of simple circuitry which apparently conforms well to their logic theory. Hence, at Essex, we have a deep conviction in the need and value of practical construction as an aid to a deeper understanding of hardware design.

To support hardware design, an in-house VME prototyping kit has been produced which facilitates construction work at a component, chip and systems level. Examples of assignments offered are the design of a DRAM controller using Altera EPLD chips and an A/D interface. In addition, project work such as a vision pre-processor engine and a smart ultra-sound proximity detection system have been hosted by this system.

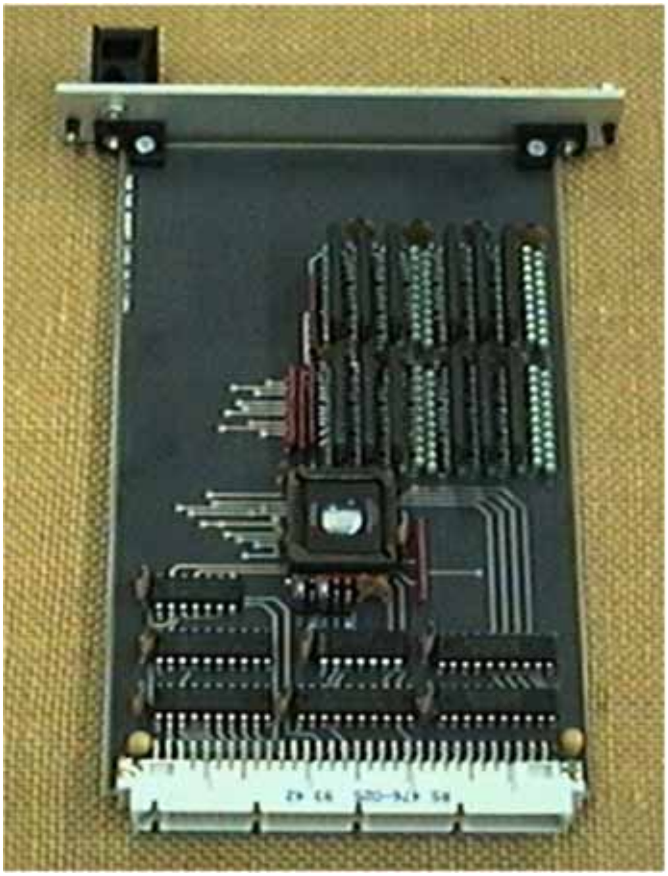

Photo 4 - Altera DRAM Student Assignment Board

3.2.2 Basic Systems Programming

Laboratory assignments in this area include an introduction to software in the laboratory based around programming the robot chassis emulator (in C and assembler) to control switches and stepper motors (both interrupt & polled I/O). Another assignment requires the student to program a voice synthesizer (chosen for its simplicity). This assignment introduces the notion of semaphores, process synchronization and teaches them structured programming methods based around Unix-style device drivers.

3.2.3 Operating Systems

Until recently, it was difficult within our department to provide students with direct access to operating system primitives without interfering with others. Hitherto, such assignments were simulated. The elegance and academic soundness of VxWorks allows that access. Assignments are being built that allow the student to "substitute their own code for intrinsic OS functions" experiment with scheduling, queuing and, most importantly, functionality that is time critical.

3.2.4 Data Communications

Network experimentation also can interfere with others, and on a grand scale. The laboratory both provides access to very low level network functions inaccessible by students elsewhere, and prevents access outside the confines of the Laboratory of such dangerous traffic. For example, one experiment graphs the efficiency of the network under various traffic requirements (length and frequency) against background loading on the contention based ethernet.

3.2.5 Artificial Intelligence

One of the most exciting aspects of the facilities described is the potential for practical experimentation in some of the latest AI techniques hitherto only available to students as theories or in simulation. To this end we have ported CLIPS and two implementations of the Predicate Logic based language Prolog to VxWorks. AI topics include: Reactive Planning in which plans are dynamically generated in the light of changes in external state; Machine Learning methods such as Genetic Algorithms and Neural Networks where computer systems can "learn" a desired "behaviour" in response to some kind of "training" or positive and negative stimuli from the environment; Machine Vision; Distributed AI in which several autonomous systems may co-operate in some common mission such as providing a map of an area.

3.2.6 Software Engineering

The laboratory provides a superb infrastructure for software engineering utilising both Unix based CASE & PC tools. In addition, the need for students to work in teams provides them with a requirement to adopt good software engineering practices. VxWorks itself provides a very good example of a well designed product, which demonstrates the virtues of structure, documentation and programming discipline.

3.2.7 Machine Vision & Virtual Systems Technology

The robots (and bench based robot emulators) are equipped with simple android-heads comprising a pair of low-cost 256x256x8 bit cameras[6] with 2 degrees of freedom plus vergence control. These are used to provide both classic vision projects and, together with associated viewing/control interfaces, provide a mechanism for virtual-presence (tele-presence) experiments. The high-level simulator, previously described also provides a means to generate virtual robot worlds in which students can interact and further develop. To date telepresence has only been used in support of project work and connecting the robot simulator to an immersive VR interface is the subject of a current project.

3.3 Research Project Work

Mobile robots are still at a very early stage of their technical evolution and thus offer a great deal of potential for R&D work. Projects undertaken in this laboratory range from undergraduates (3rd year) through to postgraduate (M.Sc & Ph.D) and industrial work. Some examples of current projects include:

3.3.1 Robot Control Architectures

A number of research projects have examined aspects of intelligent machine control. One of the first projects investigated fuzzy behaviour based control architecture & languages. This work was originally undertaken by Christos Voudouris as part of an M.Sc [11]. It concerned the development of a "hierarchial fuzzy architecture" for controlling mobile robots based on the type of behavioural AI paradigm fostered by the "Corsendonek meeting" [10]. The Voudouris architecture allowed competing robot sub-behaviours to be active in parallel, having a continuous but weighted influence on the overall robot behaviour. In addition to developing and demonstrating a behavioural fuzzy engine controlling a real mobile robot, the student developed a related language with a pre-compiler that produced gnu C from a high-level fuzzy logic behaviour based description. This work is being progressed as part of a number of industrially sponsored projects to control both land and underwater vehicles. A number of papers have been published on this work [11, 12]. More recently the work has been applied to the control of agricultural robots [20] for tasks such as crop-cutting or acting as an assistant to a farm worker by recognising, visiting and collecting items with minimal guidance. In addition, learning mechanisms based on using GAs to modify fuzzy rule sets are being investigated [24]. Other projects have focused on vision, in recognition of the fact it is key sensor in mobile robot systems. A system for recognising hay bales in a field has been developed whilst another vision project concerned the development of a novel means of determining relative locations within a field [21, 22]. An interesting view of machines which regards buildings as machines that we live inside has given rise to a project on Intelligent Buildings. The aim is to combine embedded-computers, data-networks and AI techniques to produce buildings that efficiently care for their occupants with a minimal amount of supervision!

3.3.2 Robot Simulation

Industry has for some time made widespread use of simulation (eg flight simulators, chip simulation, RTOS kernel simulation). Whilst simulation has some well known limitations, particularly in AI work,

[6] manufactured by VVL Ltd

when used cautiously and thoughtfully it can be a great asset. In this spirit a number of M.Sc students (Paul Marriott, Calab Ying, Calvin Ching, Davide Diemmi) and a 3rd year B.Sc student (G.G Wong) developed a high level mobile robot simulator over the past few years [13, 14]. The simulator and toolkit originally known as VirtualRobots and later SPREAD uses the widely used distributed processing C library, PVM (Parallel Virtual machine), to provide a simulation of mobile robots in which performance is maintained essentially independent of robot numbers and environment complexity by distributing the robot processes across a network of computers[14]. Current work is looking at distributed synchronisation, the integration of real-hardware and compatibility with HLA. This simulator now forms the core architecture for the UK's EPSRC and the Centre for Marine and Petroleum Technology Core Simulation Engine project [23]. It aims to enable simulation of underwater vehicles in an environment that mixes real and simulated components, virtual reality techniques and detailed mathematical modelling. It involves Liverpool, Heriot-Watt, Southampton and Newcastle Universities plus several companies in the offshore industry including Lockheed and Rockwater.

4.0 Evaluation

The laboratory accepted its first students in September 1993 and at the time of writing, it has been running for two years. Initially[7], 12 host/bench emulator pairs and 4 mobile systems in combination with the campus network facilities are servicing the needs of some 300 undergraduate and postgraduate students, providing approximately 6000 student/hours access per academic year. Up to 55% of this access is attributable to the extensive use of networks and simulators. Clearly, the innovative application of these tools offer a significant increase in laboratory utilization resulting in cost savings which could be availed of by any higher educational establishment adopting this approach. Student feedback have shown it a most stimulating environment. Other benefits to the university include industrial sponsorship and collaborative project work. The laboratory has attracted almost £500,000 worth of donated equipment and software from industrial companies. It has led to project work with organizations such as the EPSRC, BT and the Centre for Marine and Petroleum Technology. Some of these contacts have led to national educational deals and some companies have sponsored prizes and research scholarships. The laboratory infrastructure has already directly contributed to the production of numerous research papers on topics ranging from fuzzy control to simulation. Other benefits include increased university publicity which has aided student recruitment. For instance, the innovative nature of this laboratory has led to it being featured in national UK television and newspapers and many intending students apply for places in the department specifically because of the impression made on them by the laboratory.

6.0 Summary

An innovative *network-centric* laboratory environment which *integrates* hitherto separate computer science strands at the University of Essex around a *mobile robots theme* has been described. It comprises a unique combination of physical systems, networks, simulators and cross-development tools, resulting in a substantially more *cost-effective* teaching solution than the traditional laboratory it has replaced and differing radically from a conventional PC/workstation programming or CAD laboratory. It utilises state of the art concepts and tools such as multi-media, broadband networks, OOS, PLDS and RTOS to allow the provision of a highly modularised assignment construction and network accessible infrastructure with maximum flexibility and minimum complexity. The laboratory has spearheaded both academic and commercial arrangements which are now available to the wider UK higher education community. From conception to completion this laboratory took almost 2 years of intensive planning and construction from a team of 8 academic and technical staff. Work is ongoing with new university laboratories and linkages being continually created (eg Virtual-Reality Applications, Systems & Environments Laboratory). Finally, whilst much of this paper has dwelt on the technical, educational and financial benefits we would like to end by mentioning the immense fun and personal satisfaction we derived from this project; having to persuade students to spend less time working on assignments was a new but very welcome experience!

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[7] Since writing this paper a fleet of 20 micro-robots have been built to support a new degree scheme in “Robotics & Intelligent Machines”

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NOTE: This paper was originally written using Framemaker. In rebuilding this paper many of the original files could not be read so various diagrams and illustrations were lost while converting it to WORD and PDF. However, the text is accurate.