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Development of Laboratories and Computing Facilities

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The development of various engineering laboratories at the Nanyang Technological University and their relation to the building developments are discussed. The different approaches and concerns of each School of Engineering are illustrated. The paper also discusses the goals and strategies in the planning of a campus-wide IT infrastructure. This is followed by a discussion on the revised goals and strategies for the necessary phased expansion and upgrade of the IT facilities to meet the growth in computing needs.

INTRODUCTION

UPON THE completion of construction of major building works and services, further steps were necessary before the buildings and services could be put to good use for teaching activities. Among such further steps were the setting-up of laboratories and computing facilities. There were thus two major stages in the development of laboratories and computing facilities.

The first stage was the creation of adequate floor space for the accommodation of the proposed facilities. For the Engineering Schools, the floor space required for laboratories and computing facilities constitutes a major portion of the total floor space of the building project. The funds and the implementation of this first stage were included as part of the relevant building development works, which are discussed in the paper 'Physical Development and Planning of the Campus' by Phang Kok Wai in this issue. General utility services and laboratory furniture were also installed at this stage. The general utilities cover normal building-services, such as general air-conditioning, mechanical ventilation, lighting, water supply, sanitation, fire-protection services, security systems and the like. Ducting or trunking for the installation of telephone and computer cables were also included with the building-services installations. However, specialized requirements which could not be incorporated at this stage would have to be dealt with at the following stage when specific laboratory or computing equipments are installed.

The second stage in the development of laboratories and computer facilities dealt with the provision and installation of the equipment specific to the various laboratories and computer facilities. Such equipment is used directly for the teaching and research activities and does not form part of the normal building installations. Funds for laboratory and computing equipments were identified separately from those for the building works. The level of funding for such equipment depended on the courses of study and the respective number of students.

VARIED REQUIREMENTS AND APPROACHES

The type of laboratory equipment varies widely from school to school and within each school itself. Due to the diverse nature of the equipment and the specific needs which only a particular school is familiar with, the acquisition and installation of teaching and research equipment is administered by the deans of the respective schools. As the detailed needs and problems encountered are different among the various schools, the different approaches reflecting the diversity of problems are discussed separately in the following sections based on input from the deans of the various Schools of Engineering.

The planning, acquisition and installation of computer equipment and network also requires specialized knowledge. This area of work is managed by the Computer Centre. Discussion on this aspect of development is covered separately in a section contributed by the Director of the Computer Centre.

THE SCHOOL OF CIVIL AND STRUCTURAL ENGINEERING (CSE) LABORATORIES

Overall planning of new laboratories

The design of a completely new tertiary institution such as the Nanyang Technological Institute

(NTI), the predecessor of the Nanyang Technological University (NTU), is a rare occurrence. The commitment of the NTI/NTU to professionally oriented education requires that schools and their staff foster links with industry, and one of the means of achieving this is to provide suitable and up-to-date laboratory testing facilities. The NTI/NTU laboratories should also serve to encourage present and future links with industry.

The School of CSE had the privilege of planning for its laboratory facilities well in advance of the preparation of the architectural blueprints for the NTU campus. In this respect, many laboratory facilities of overseas universities and engineering research stations were visited to gather information on the design of the School's laboratories to meet the needs of teaching, research and industrial service.

In addition, the School also took advantage of visits by many prominent civil engineering academicians to seek their advice on the planning of the School's laboratory facilities. The comprehensive planning also took into consideration the co-operation and links with industries on special research and development projects.

General guidelines for laboratory design

Although it may not be possible to predict accurately the needs of industry and the state of the art of engineering technology in the coming decades, it is possible to design laboratories so that they have sufficient flexibility to adapt to these changes. For example, this flexible approach implies that there should be sufficient space and ceiling height to accommodate any equipment, models or test specimens that are likely to be in the laboratories in the foreseeable future. To optimize space utilization, built-in facilities within an individual laboratory should be restricted to the minimum. There should be sufficient power outlets and concealed conduits for services to enable equipment to be rearranged easily within a laboratory without necessitating additional pipe or cable installation.

Feedback from users of laboratories visited indicated thatsufficient storage space should be provided for each laboratory. In general, the cost of providing storage space is a lot less than that for laboratory space. Due considerations should be given to easy access to laboratories and the handling of materials and equipment within them. This is particularly necessary for those laboratories where large or heavy machinery is likely to be installed. Ideally, it should be possible for a delivery truck to be driven into a laboratory and off-load items using an overhead travelling gantry crane which should serve all areas of the laboratory.

Equipment and machinery require regular maintenance and certain items need to be fabricated in-house for use in most laboratories. Therefore, a centralized workshop is useful to provide complementary support to other laboratories of the School.

Two examples are cited as follows to illustrate the School's effort in implementing the above guidelines in the design of the School's phase I laboratories.

Illustrative examples

Heavy Structures Laboratory. The structural testing area is the most important part of this laboratory, and consequently much thought, investigation and discussion have gone into this aspect of the laboratory design.

In order to comply with the flexible approach to laboratory design, it was decided to use a strong reaction floor for the main testing area. A floor of this type is designed to withstand heavy vertical loads at a large number of loading points, thus facilitating the testing of structural elements in all parts of the testing area. For a number of reasons, it was decided that the structural form of the strong floor should be the hollow section type, with a basement below the main reaction floor. The loading points are provided by holes through the reaction floor. For greater flexibility in positioning the test rigs, two different hole-spacing systems are adopted, i.e. at 1.0 m and 0.5 m centres-to-centres. Each of the 1.0 m centre holes is capable of resisting a vertical pull-out force of 40 tonnes. The 0.5 m centre hole is capable of resisting 20 tonnes. This loading requirement has resulted in a concrete floor with a thickness of 1.2 m. In addition to the strong floor, a special provision in the form of a sunken basement was made to house a 500 tonne universal testing machine. Facilities were provided for the handling and drying of aggregates and for casting and curing of concrete specimens. Figure 1 shows the set-up of the Heavy Structures Laboratory.

Hydraulic Modelling Laboratory. One of the major requirements of a hydraulic modelling laboratory is a large and steady flow of water. A self-contained recirculating water supply system must also be incorporated as an integral component of the laboratory. The water supply proposed for the laboratory is essentially a direct pumping system (i.e. models are fed by pumps directly from a sump) with some provision for constant head investigations. Around the perimeter of the laboratory is a deep channel sump, which is connected to shallower return channels running along and across the laboratory. Provision was also made so that flows from these return channels may be diverted to a weigh tank for flow calibration prior to discharge to the sump channel. There are provisions to fit stop boards and weirs atstrategic points in the channels for isolating certain sections and to supplement additional flow measurement facility. A constant-head facility is provided at one end of the laboratory where fixed pumps are installed to pump water from the channel sump to an elevated tank. In the development of the conceptual design of the laboratory, built-in facilities —model basins, wave

Fig. 1. Heavy Structures Laboratory.

tanks, etc.—have not been included as it was felt that these may hinder the future development of the laboratory. However, it is envisaged that both the return channels and the sump channels in conjunction with suitably placed stop boards could provide facilities for some open channel investigation and current meter calibration. Thus, attempts have been made to ensure that the design is sufficiently flexible to adapt to future trends and needs and at the same time to provide sufficient facilities for meaningful hydraulic model studies.

Laboratories and field testing facilities

Laboratories. The School has at present the following laboratories: Geotechnics, Surveying, Structures, Construction, Computer Aided Design and Drafting (CADD), Wind Tunnel, Hydraulics, Environment and Transportation. These laboratories comprise both typical classroom-based facilities as well as research capabilities. A brief description of each laboratory is given in the detailed list of CSE laboratories in Appendix A.

CSE Experiment Station. The School has, through the unique second-year curriculum subject, the In-House Practical Training (IHPT) programme, expanded on the laboratory facilities to meet the needs for research activities. In the past, the IHPT project has been implemented yearly as an individual construction project to build in a piecemeal fashion different modules of the CSE Experimental Station Complex over a 50 m^2 site. This complex is to cater for research needs in the areas of study in construction, environmental, geotechnical and hydraulic engineering. Figure 2 shows a sketch of the different modules of the Complex. To date, the CSE Experiment Station Complex has the following modules:

1. A weathering chamber capable of simulating and accelerating the extreme heat and humidity as well as other environmental elements of the tropical weather conditions. The chamber can be used to study the performance of building and structural material including facade curtain walls and other external wall finishing systems.
2. A water-jet cutting facility to study its applications on various engineering materials.
3. A tide-wave basin for the physical modelling of coastal projects such as large-scale testing of tidal flushing, wave actions and beach sand movements.
4. An experimental plot with a rainulator for hydrological simulation of rainfall run-off processes over landforms.
5. A geotechnical field testing facility that features a 4 m deep reinforced concrete trench to conduct large-scale geotechnical testing.
6. A high-temperature environmental oven to study the reuse of incinerated waste materials for new applications in various civil engineering fields.

Destructive Testing Facility. Currently, the School has embarked on an extension programme to construct a new destructive testing facility that features a strong floor serving as a reaction base to conduct load-testing on life-size structures at the serviceability and ultimate load bearing limit states. During the annual IHPT period, second-year students will construct a structure and eventually load-test it to failure to compare actual structural behaviour up to failure load to that predicted by

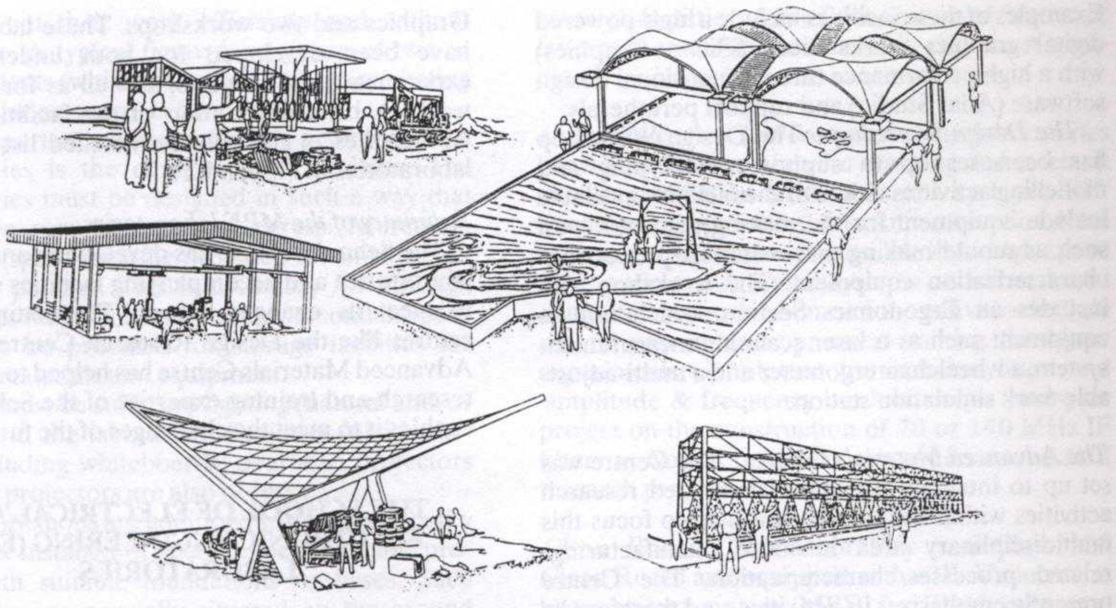

Fig. 2. Different modules of the CSE Experiment Station Complex.

theoretical analysis. Outside the IHPT period, this new testing facility will also cater to the research needs on structural instrumentation, design safety in construction and building appraisal procedures of constructed structures.

Summary on CSE laboratories

The various laboratories, the CSE Experimental Station Complex and the new Destructive Testing Facility of the School of CSE form a very sizable research and testing complex, which is considered to be one of the largest in South-East Asia. Coupled with the specialized expertise of its staff, the School is poised to undertake challenging civil engineering research to provide innovative solutions to the pressing problems of industry.

THE SCHOOL OF MECHANICAL AND PRODUCTION ENGINEERING (MPE) LABORATORIES

Planning approach

One of the most important objectives in the physical development and planning of the laboratory facilities in the School of MPE has been to ensure that the facilities are up to date with the current and future needs of industry. This also highlights one of the main tasks in the planning for laboratory facilities in a technological university like the NTU. As technology itself is constantly undergoing changes and development, the planning and development of laboratory facilities itself becomes an ongoing process. This is particularly so in the manufacturing industry environment, where the vital need to remain competitive results in the adaptation of newer design and manufacturing methods every few years—a point well highlighted by the electronics manufacturing industry.

The challenge for the School of MPE in terms of the physical development and planning of its facilities is thus to have the foresight and flexibility to adapt to the necessary and ongoing changes. Careful planning during the development of the NTI has ensured that the present facilities already have sufficient basic infrastructure facilities like minimum floor strength, ceiling height, installation access and electrical power outlets for future development. The NTU is presently undergoing a major and considerable increase in the volume of research activities in the Engineering Schools, and this is the major development being implemented in this respect. The main task is to achieve a compatible balance between facilities for ongoing undergraduate experiments and facilities to strengthen the research activities of the School. Two examples are given below to illustrate the School's approach in development and planning to meet this task.

Illustrative examples

The Design Research Centre. The Design Research Centre has been recently established to develop and upgrade design expertise, skills and competence, and to create a centre for design, to interface design and manufacturing in collaboration with industry. The establishment of the Centre's facilities also helps to emphasize the School's considerable effort on design technology. Two main facilities have been developed for the Centre.

The Design Laboratory—The laboratory has been developed to support conceptual design activities, for both research as well as training and education. In order to effectively integrate the activities in the laboratory, it has its own integrated computer workstation hardware and software.

Examples of these facilities include a high-powered digital graphics workstation (Silicon Graphics) with a high performance three-dimensional design software (Alias Studio) and support peripherals.

The Design Workshop—The Design Workshop has been set up to support prototyping and modelling activities. Some of the facilities available include equipment for the making of prototypes, such as mould-making and materials-processing/characterization equipment. The workshop also includes an Ergonomics Section, which houses equipment such as a laser scanning measurement system, a wheelchair ergometer and a multi-adjustable work simulation station.

The Advanced Materials Centre. The Centre was set up to integrate the materials-related research activities within the school, and help to focus this multidisciplinary area in more manufacturing-related processes/characterization. The Centre presently emphasizes its activities, and therefore its development of facilities, in three areas. The Centre itself comprises three main sections, with each section equipped to support the following technologies.

Powder Technology—Included in this area of research is the production of powder metallurgy based metal matrix composites by injection moulding, as well as high deformation methods. The major acquisitions have been a 50 tonne metal injection moulding machine, a 200 tonne metal matrix composite powder extrusion machine, a plasma spray unit, a particle analyser, porosity measuring facilities and a high-temperature X-ray diffractometer.

Polymer Composites Processing Technology—The processes emphasized in this area include high-pressure autoclave processing, microwave curing techniques and thermoforming of thermoplastic composites. Facilities acquired include a laboratory autoclave unit, a continuous microwave curing system, a prepreg unit as well as a thermoforming press.

For polymer characterization work, a complete thermal analysis unit comprising of a differential scanning calorimeter, a thermogravimetric analyser and a dynamic mechanical analyzer was acquired.

Surface Engineering—The focus in this area includes laser scribing and surface hardening. The main facilities acquired include plasma nitriding units, plasma torch units and a hot isostatic press. Surface characterization facilities such as scanning electron microscope, image analyzer and metallography facilities are also present.

Laboratory facilities

Aside from the two centres, the School of MPE at present has the following laboratories: Fluid Mechanics, Thermodynamics, Energy Conversion, Wind Tunnel, Instrument and Control, Automation and Robotics, Metrology, Strength of Materials, Mechanics of Machines, CAD/CAM, Graphics and two workshops. These laboratories have been developed for both undergraduate experiments and projects, as well as for research work. A brief description of the facilities in the laboratories is given in the detailed list of MPE laboratories in Appendix B.

Summary of the MPE laboratories

The School of MPE has developed considerable laboratories and accompanying facilities sufficient to meet its changing needs. The setting up of centres like the Design Research Centre and the Advanced Materials Centre has helped to focus the research and training expertise of the School, and enables it to meet the challenges of the future.

THE SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING (EEE) LABORATORIES

Planning approach

The School of EEE aims at preparing its undergraduates to be competent engineers who can play an effective role in industry upon their graduation.

The curriculum structure and courses conducted by the School have been designed and developed to achieve the objective of the NTU, i.e. to produce well-trained engineers to meet the needs of industry and to help enhance the national well-being of Singapore.

To achieve this objective, the laboratories within the School were carefully designed and equipped with modern facilities to support undergraduate teaching and postgraduate and staff research activities. One of the important consideration in setting up new laboratories in our context is the capability to handle a large group of undergraduates, typically in the range of 500–700. One possible approach is to organize laboratories into two main categories:

- Teaching laboratories and workshops
- Research and project laboratories

General guidelines for laboratory design

Teaching laboratories and workshops. Teaching laboratories are established to conduct experiments on fundamental concepts. A number of experiments related to each subject of study are set up. In these laboratories, portable equipment is set up on benches for individual experiments. The students work in small groups and a few groups of students work simultaneously on the same experiment. This facilitates the supervision of the students as well as the organization of these experiments.

The space requirements for these laboratories is based upon the maximum number of students attending at any one time. Depending upon this, the laboratory size may, in general, vary anywhere between 50 m^2 and 300 m^2. The space requirement for each group of students performing an experiment is based upon the fact that they should be able to carry out their work efficiently and without hindrance. A typical figure for a group of two or three students (which includes bench space, seating and circulation space) is 5 m^2.

An important consideration in planning these laboratories is the circulation of students. The laboratories must be designed in such a way that they have easy ingress and egress. Moreover, sufficient space must be provided for uncluttered and easy passage. This is necessary for efficient working as well as for safety of the personnel. Space must also be provided for storage facilities for teaching materials and equipment.

There must be sufficient lighting (natural and/or artificial) in the laboratory. Facilities for instructions including whiteboards, overhead projectors and slide projectors are also necessary.

The workshops are equipped with items of bulky apparatus installed at specific locations and provided with suitable foundations or bases. Such workshops are normally situated on the ground floor of a building. Since the cost of such apparatus tends to be high, they must be shared by as many students as possible.

Research and project laboratories. The main purpose of these laboratories is to provide research and development facilities for the students. These laboratories could be in the form of small rooms where individual tasks or research-oriented projects are carried out, and where apparatus is usually set up for long-term observations. Alternatively, they could be housed in bigger rooms where a number of projects are set up on individual benches. In these laboratories, the personal space requirements are about 10 m^2, which is higher than the requirement in teaching laboratories. Most of the design considerations applicable to the teaching laboratories are also applicable in the case of research laboratories.

Some of the issues which need special consideration in the design of a research laboratory, are mentioned below:

- *Flexibility*—The nature of research can change in unpredictable ways. In a specific topic, research itself may uncover new approaches or points of emphasis. The programmes of research and development may alter their priorities.
- *Safety*—Sufficient safety must be provided against electrical shock, fire, explosion, exposure to radiation, toxic chemicals and other such hazards. This assumes even greater importance if the research worker has to work for long hours in a solitary environment.
- *Quality of environment*—Environment should be such as to promote communication among scientists and research workers who are working in the same discipline.

Illustrative examples

Three examples are cited below to illustrate the School's effort in establishing teaching and research facilities. A brief description of the rest of laboratories within the School is given in Appendix C.

Communication Laboratories. The laboratories provide facilities mainly for teaching and research in communication principles and systems, RF/microwave engineering, data communication, local area networks, radio systems, teleview, high-speed fibre optic transmission systems and fibre-based computer networks. Some of the activities include second-year in-house practical training, third-year experiments on 'slotted transmission lines' and 'amplitude & frequency modulation', a third-year project on the construction of 70 or 140 MHz IF filters as well as final-year, postgraduate and staff research projects.

Clean Room. This laboratory is a Class 100 Clean Room and equipped with a III–V molecular beam epitaxy system (MBE) for III–V compound semiconductor material growth and device research, an electron cyclotron resonance microwave plasma enhanced chemical vapor deposition system (ECR PECVD) and a high-pressure microwave plasma-enhanced chemical vapour deposition system (HP PECVD) for diamond thin-film growth, diamond semiconductor research and silicon carbide thin-film device research, a DC filtered arc discharge deposition system for diamond-like-carbon (DLC) film research, a reactive ion etching system (RIE) for dry etching, a chemical bench for wet etching and other chemical processes, a rapid thermal chemical vapor deposition system (RTCVD), a plasma-enhanced chemical vapour deposition system (PECVD) and a low-pressure chemical vapour deposition system (LPCVD). For device patterning, there is a photolithography room inside the Clean Room where a mask aligner and a photoresist spinner and other related equipment are housed. It is a fully equipped laboratory for various materials growth and device fabrication research.

Network Technology Research Centre (NTRC). This has been established by the NTU in joint partnership with Digital Equipment Singapore Pte Ltd with the objectives of (i) contributing to the success of IT2000 Intelligent Island implementations, particularly in the areas of network information infrastructure and network services, (ii) contributing to making the NTU an intelligent campus, and (iii) becoming a centre of excellence for applied R&D, prototyping and system integration in communication technologies. Some of the research areas pursued by the NTRC include network administration and management, network security, network services, wide-area applications, interfaces, transmission systems, modelling, performance analysis and data communication devices. Excellent computing and networking facilities are available in the NTRC to enable it to function as a test centre for network standards conformance and interoperability. Besides its own full-time R&D engineers and laboratory technicians, the NTRC also taps the expertise of the academic staff and other research centres in the NTU to work jointly on network and communication technologies. Relevant postgraduate and final-year projects are also carried out in the NTRC. Research activities include design of an LAN-ATM gateway, a multimedia electronic mail system, an integrated radiologist network, an integrated network management for NTUnet, network access services for Teleview, etc.

Summary of EEE laboratories

The various teaching and research laboratories established within the School of EEE over the years have provided it with some excellent facilities for producing well-trained engineers for Singapore and South-East Asia.

DEVELOPMENT OF COMPUTING FACILITIES; IT INFRASTRUCTURE

Planning IT infrastructure

In 1985, the NTU (then the NTI) prepared and submitted a fund request paper to the Ministry of Finance outlining its computing requirements for the period 1986–1990. The budget request submission was timed to cater for the implementation of a new information technology (IT) infrastructure in the new premises which were expected to be ready in early 1987. The main objective was to design an IT infrastructure which could best serve both the academic and administrative computing needs, as well as cater for easy communications among the campus community, and access to the various distributed computing facilities on the campus. The fund request paper also included an Information System Planning (ISP) report which was completed earlier on. This ISP report spelled out the Univeristy's critical information needs in the form of a data model and data dictionary which served as a blueprint for the implementation of a comprehensive and integrated information system for the NTI.

It was realized at an early stage of the planning in 1985 that academic computing needs would change with advances in technology and that each of the Engineering Schools within the NTI would have very different computing requirements. It was foreseen that without central planning, computing facilities would quickly proliferate and be duplicated without any economy of scale, while computerized applications would be implemented without regard for the need to share and consolidate data. Hence a campus-wide IT infrastructure and information system planning were co-ordinated by Computer Centre with the following strategies.

- Let each school have their own dedicated computing resources to meet their own special needs, particularly for CAD/CAM/CAE purposes.
- Centralize general-purpose computing resources for supporting teaching and research as sharing of such resources makes economical sense.
- Adopt a central and integrated database approach as far as possible for the implementation of comprehensive information system for supporting NTI's administration, and for ease of data sharing, control and integration.
- Adopt a student to personal computer (PC) ratio of 10:1 and a staff to PC ratio of about 1:1 to enhance personal productivity.
- Implement a campus network which would facilitate easy access and sharing of computing resources and yet would segregate the academic computing facilities from the confidential administrative computing facilities.
- Provide campus-wide office automation to enhance communications among the students, the academic staff and the administrative staff.
- Facilitate communications with overseas universities by linking to the international academic network known as Bitnet.

Initial IT infrastructure (phase I)

Following the Ministry of Finance's approval of funding for NTI's IT requirements, tenders were invited in 1986 for the supply of computing facilities to help realize the above-mentioned strategies. DEC was awarded the tender, and by mid-1987 all the required computing facilities were installed and running. NTI's computer network, called NTInet, became the first successfully implemented campus-wide network in South-East Asia, and acted as an catalyst for other institutions of higher learning in the region to follow suit. A simplified NTInet is shown in the diagram Fig. 3.

NTInet consisted of a 10 Mbit/sec broadband Ethernet main trunk which was extended by baseband Ethernet cables into all the offices, laboratories, computer terminal rooms and several large lecture theatres. It linked over 1000 PCs and workstations, and about 150 shared printers. The PCs, workstations and printers were distributed into 14 subnets with each subnet having its own network server providing network file and print services. The main trunk of NTInet was about 8 km long, while the extension cables to the PCs, workstations and printers covered a length of over 120 km.

Besides linking the various computing facilities in the schools in NTI, NTInet also provided easy access to the central academic and administrative computing facilities. The central academic computing facility consisted of three VAX 8820s, while the administrative computing facility consisted of one VAX 8520 and one VAX 8250.

NTInet's main trunk provided two data channels and six video channels. The two data channels were used to separate the computing facilities used by the students and academic staff from those used by

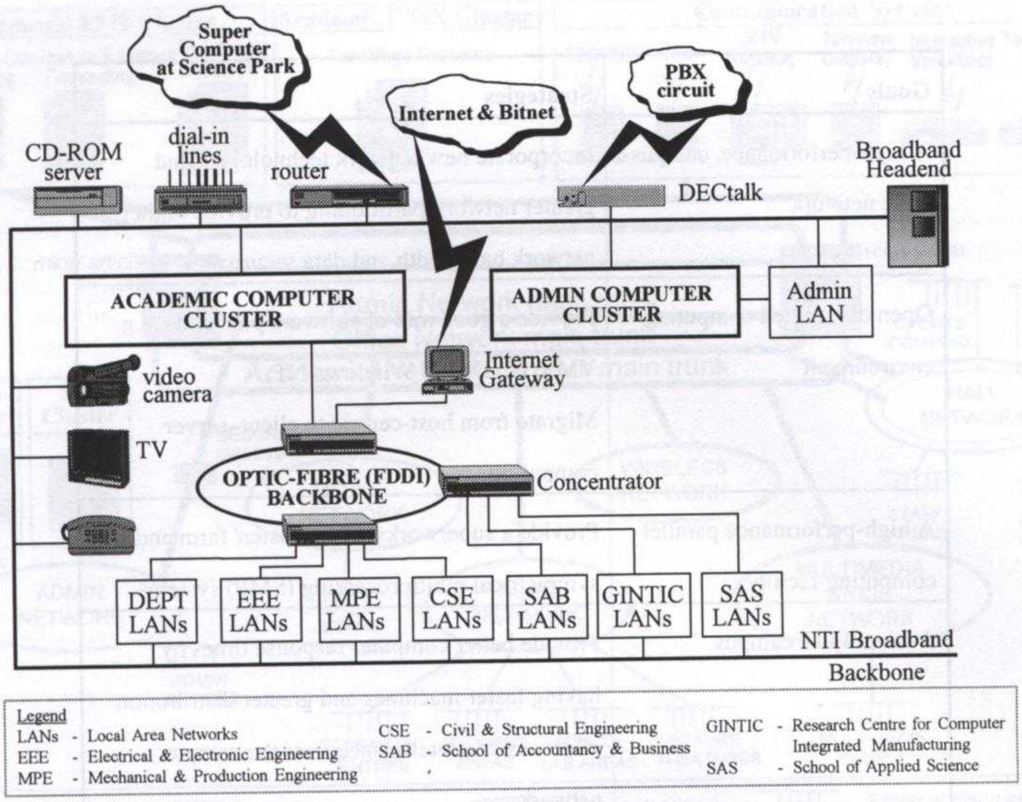

Fig. 3. NTI campus network—phase I.

the administrative staff. This security measure helps to prohibit unauthorized users from easily getting into the confidential administrative computing systems. To facilitate data flow or message routing between the administrative staff and the rest of the campus community, a secured private network link was provided between the academic and the administrative computing clusters.

The video channels on NTInet's main trunk are used for the transmission of video from one lecture theatre to another. This is useful in the case where a lecture theatre was unable to accommodate all the participants.

From 1987 to 1992, the student population continued to increase rapidly. During this period, the computing facilities were upgraded to cater for greater computing demands. More PCs and workstations were acquired and put on NTInet. NTInet was enhanced with a 100 Mbits/sec fibre-optic (i.e. FDDI) main trunk to provide a large bandwidth 'highway' as shown in Fig. 3. Two VAX 9000s were acquired and added to the central academic computing cluster. In 1991, NTInet was renamed NTUnet to reflect the University's new name.

IT infrastructure expansion and upgrade (phase II)

By late 1992 it was clear that further IT infrastructure expansion was needed to cater for NTU's phase II and future development. A committee was appointed by the President to examine new IT technologies and to propose a new IT infrastructure which would cater for NTU's needs for the next five years. The committee consisted of representatives from some of the schools and was chaired by the Director of the Computer Centre. The Committee completed their report in 1993. The report, entitled 'Technology Strategy for NTU Computing System', was endorsed by the University. A fund was approved in the same year by the Ministry of Finance to implement the new plan.

Goals and strategies for enhanced IT infrastructure. The 'Technology Strategy for NTU Computing System' report outlined the major goals and supporting strategies shown in Table 1 to guide the implementation of an enhanced IT infrastructure:

Upgrade strategies for NTUnet. The upgrade strategies to enhance NTUnet into a high-performance network which can cater for NTU's phase II and future development include the following actions:

- Reduce the number of PCs and workstations on each Ethernet network segment by partitioning the NTUnet into a greater number of Ethernet network segments. This strategy provides NTUnet with greater data bandwidth to support a greater number of computing nodes and users.
- Improve network data security by having separate network cables to serve academic staff and

Table 1

Goals	Strategies
A high-performance, campus-wide network	Incorporate new network technologies and greater network partitioning to provide higher network bandwidth and data security
Open distributed computing environment	Provide a good mix of software platforms, e.g. VMS, UNIX and Windows-NT; Migrate from host-centric to client–server computing.
A high-performance parallel computing facility	Provide a superworkstation cluster/ farm and symmetrical multiprocessing (SMP) systems.
A friendly IT campus	Provide better computer response times by having faster machines and greater distribution of processing intelligence over the campus network; Provide better integration of desktop and host-centric applications; Provide more easy-to-access information services to support workgroup and curriculum computing.

students. This cable separation ensures that students cannot easily tap the data transmitted by staff over the staff subnets.

- Consolidate the many remote network servers by centralizing them and replacing them with fewer and more powerful new servers. This consolidation move simplifies the efforts and manpower needed to manage these network servers.
- Replace old network hubs with new ones which have high internal bandwidth, switching capability and support for future ATM (Asynchronous Transfer Mode) technology. The new network hubs further help to increase the overall data bandwidth of NTUnet and cater for future multimedia applications which demand very high network bandwidth.

Enhanced IT infrastructure. The enhanced IT infrastructure as implemented in mid-1994 is shown in Fig. 4. NTUnet is upgraded to a three-tier network. Its first-tier segment, or main trunk, has a bandwidth of 400 Mbits/sec and can be further easily upgraded to 1200 Mbits/sec if necessary. The main trunk is extended into three second-tier 100 Mbits/sec fibre-optic (FDDI) networks, namely the Administration Network, Office Network and Academic Network. Computing servers are distributed across these four networks to ensure reasonable computer response times for the various computing applications as shown in Table 2.

The three fibre-optic networks are extended into multiple third-tier 10 Mbits/sec Ethernet segments, which run to all staff offices, laboratories, computer terminal rooms, lecture theatres and student halls of residence.

Convenient network connection points are provided in computer terminal rooms and student halls of residence to enable students' notebook computers to be easily plugged into the campus network.

The enhanced NTUnet incorporates switching network hubs which accommodate future ATM modules. This ensures that NTUnet can be easily enhanced in future to a fully ATM-compatible switched internetwork to facilitate higher network bandwidth for multimedia transmission.

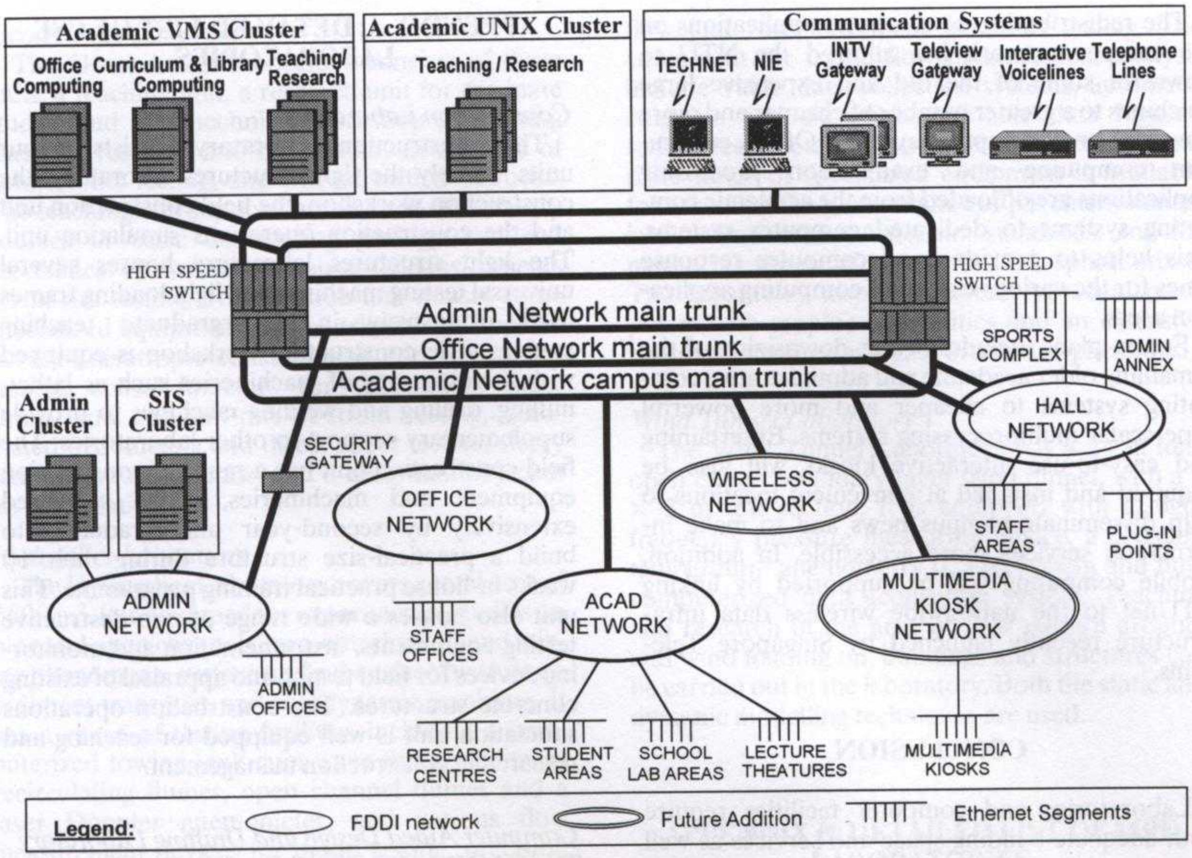

Fig. 4. NTU's enhanced IT infrastructure—phase II.

Table 2

Network class	Computing servers and applications	Permitted users
Administration Network	Computing systems for student database, staff database, examination processing, financial management and payroll applications.	Authorized administrative staff
Office Network	Computing systems for staff office computing, workgroup applications and in-house software development.	All staff
Academic Network	Computing systems for student curriculum management, Library management, communications computing, and student workgroup applications; and Computing systems for instructional computing and research.	All staff and students

The redistribution of computer applications on the campus network has allowed the NTU to downsize some of the old and expensive large machines to a greater number of cheaper and more powerful small computer systems. Office, curriculum computing and examination processing applications are offloaded from the academic computing systems to dedicated computer systems. This helps to provide good computer response times for the various classes of computing application users.

Future plans include further downsizing of the remaining older academic and administrative computing systems to cheaper and more powerful superscalar multiprocessing systems. Entertaining and easy-to-use interactive kiosks will also be acquired and installed at convenient locations to help disseminate campus news and to make information services more accessible. In addition, mobile computing will be supported by linking NTUnet to the nationwide wireless data infrastructure recently launched by Singapore Telecoms.

CONCLUSION

Laboratories and computer facilities require both adequate building space and services as well as appropriate equipment. Building space together with general building services are provided for as part of an overall building program which is managed by the Office of Development and Planning with specific user input from the Schools. Equipment for teaching and research are, however, acquired and installed under the control of the respective Deans of the Schools. This is due to the nature of the equipment, which is specific to each School. Thus each School carries out detailed planning of its equipment requirements with reference to the needs of the School's courses of study and research.

Computer network and equipment are acquired and installed by the Computer Centre. In planning for the IT infrastructure, a top-down approach was adopted so that the Schools' varied computing facilities, as well as those of the administrative departments, could be easily linked together. A sound IT architecture should also take into consideration the ease of manageability and scalability of the envisaged IT infrastructure so that it can be managed with fewer human resources and can be smoothly evolved to meet the ever-growing computing needs of users. A well-planned IT infrastructure should facilitate easy incorporation of new technologies and rapid implementation of campus-wide applications such as electronic mail and discussion, student curriculum applications and workgroup applications.

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APPENDIX A: DETAILED LIST OF CSE LABORATORIES

Construction Laboratory

The Construction Laboratory consists of four units, namely the light structures laboratory, the construction workshop, the field construction unit and the construction operations simulation unit. The light structures laboratory houses several universal testing machines and light loading frames used extensively in undergraduate teaching courses. The construction workshop is equipped with a wide range of machineries such as lathes, milling, drilling and welding machines to provide supplementary support to other laboratories. The field construction unit has a range of construction equipment and machineries, which are used extensively by second-year undergraduates to build a practical-size structure during their 10 weeks in-house practical training programme. This unit also houses a wide range of non-destructive testing equipments, instrumentation and monitoring devices for field testing and appraisal of existing concrete structures. The construction operations simulation unit is well equipped for teaching and research in construction management.

Computer Aided Design and Drafting Laboratory

The CADD Laboratory is equipped with a variety of computer facilities and software packages to support the teaching, research and development activities of the School. Hardware ranges from networked PCs to high-speed workstations. Software packages cover different areas including structures, construction management, water resources, transportation, geotechnics and surveying. The computers are distributed in six function rooms: Graphics Room, PC Room (B1), PC Room (B2), Minicomputer Room, Simulation Room and Research Room. Through the DecNet networking, all computers are connected to the Computer Centre's VAX machine for access to other application packages.

Environment Laboratory

The Environment Laboratory is equipped to conduct quality examinations of solid, water and air samples as well as to carry out specialized investigations. For research use, a variety of specialized equipment is available for quick and accurate measurements of quality parameters. Some of the major facilities are a large-size walk-in refrigerator, two temperature-control rooms, a gas-chromatograph mass spectrometer system, an inductively coupled plasma system, a particle size analyser, a scanning electron microscope with a cryo system, an atomic absorption spectrometer with a graphite furnace, a high-performance liquid chromatograph, ion chromatograph and auto analyser, a pilot water treatment plant, a high temperature furnace and a rotary kiln furnace.

Geotechnics Laboratory

The Geotechnics Laboratory consists of three units: a teaching unit, a research unit for graduate studies and a geotechnical workshop supporting teaching, research and consultancy in the area of field, model testing, and triaxial testing of rocks. The teaching unit supports activities for laboratory courses in basic engineering geology and soil mechanics. The workshop houses field instruments for *in situ* testing. The research unit houses some specialized equipment such as triaxial test apparatus for anisotropic consolidation and stress path testing, consolidometers for dissipation, finite strain, and constant-rate-of-strain testing, automated oedometers and direct shear testers, slurry sedimentation columns, and a deformation jacket for rock testing.

Hydraulics Laboratory

The Hydraulics Laboratory covers a total area of 2600 m^2. It is equipped for experimental studies on pipe and open channel flows, entrainment and mixing phenomena, surface and subsurface hydrology, sediment transport, and rotodynamic machines. It has a range of testing facilities including a computerized towing tank cum wave flume, sediment recirculating flumes, open channel flumes and a laser Doppler anemometer, and various flow measurement devices for pump testing, precision instrument calibration and physical modelling of water resources engineering systems.

Structures Laboratory

The Structures Laboratory comprises two units: the structural mechanics and heavy structures laboratories. The structural mechanics laboratory houses a variety of working models simulating real structures in their various forms for teaching and research purposes. The heavy structures laboratory occupies a 60 × 24 m floor space with 10 m of headroom and is equipped with a comprehensive range of instrumentation and data acquisition equipments, together with central on-line servo-hydraulic actuation facilities such as the 500T Schenck-Trebel RBU universal testing machine, the 25T Schenck PSB material fatigue testing machine and several other Schenck and Instron dynamic actuators. Several loading frames, up to a maximum capacity of 600 tonnes, are available for static and dynamic testing of full-sized structural components and prototypes.

Surveying Laboratory

The Surveying Laboratory is equipped with wide range of precision instruments for geodetic, hydrographic, photogrammetric, construction and engineering surveying. It is supported by computing facilities with various application softwares. A few workstations are dedicated to geographic information system and remote sensing research.

Transportation Laboratory

The Transportation Laboratory is equipped with facilities and computer software to measure traffic flow and road pavement materials testing. The equipment for traffic flow measurement analysis include video data collection systems, automatic counters and classifiers, portable data loggers, radar speed meter and sound level meters. A complete range of specialized equipment is available for assessing the performance of pavement materials to British and American standards, and for measuring the elastic properties of asphalt mixes. The laboratory also has several personal computers with graphic capabilities and an extensive range of software for transportation applications.

Wind Tunnel Laboratory

The Wind Tunnel Laboratory has a 24 m long open circuit boundary-layer wind tunnel, with a 2 × 3 m test section. It is equipped with a high-frequency pressure measuring device, a constant temperature anemometry (CTA) system and fully computerized data acquisition system. Teaching and research in the area of flow pattern around, and wind loading on, buildings and structures can be carried out in the laboratory. Both the static and dynamic modelling techniques are used.

APPENDIX B: DETAILED LIST OF MPE LABORATORIES

Fluid Mechanics Laboratory

Most of the facilities in this laboratory have been equipped for undergraduate experiments on the study of the flow characteristics of fluid flow. One of the main equipments in the laboratory is the laser anemometry system. The system employs a three-beam, two-component method to measure air and water flow. It also has a fibre optics adapter for flow visualization. Some examples of ongoing projects using this facility include an aircraft lobe mixer, artificial heart valve design, and aircraft intake S-duct design. There is also a wind tunnel which is capable of both high- and low-speed testing.

Energy Conversion Laboratory

The laboratory is basically equipped for analysis of energy conversion in IC engines, transient exhaust gas emission, engine thermodynamic cycle analysis, engine performance optimization, effect of exhaust gas recirculation control, flow and wave action in inlet/exhaust pipes and the dynamics of three-way catalytic converters.

Thermodynamics Laboratory

Aside from the standard undergraduate thermodynamic facilities for pressure/heat exchange experiments, the laboratory also has a highly sensitive micro-manometer, a mini spray dryer system for converting liquid solutions to fine powder, a refrigerated bath unit and a thermocouple welder for research work.

The Strength of Materials Laboratory

The laboratory is well equipped for both research and undergraduate experiments. The major equipment are the 300 kN Shimadzu Dynamic Servopulser, a 1130 Nm Instron Dynamic Testing Machine, 2100 and 150 kN Instron universal testing machines, a 100 kN Instron Electro Magnetic Resonance Machine, a transmission and reflection polariscope, a Retra TV-Holography System and several TML Dynamics strain meters.

Mechanics of Machines Laboratory

This laboratory comprises mostly facilities for undergraduate experiments on motion and vibration. A wide range of accelerometers and vibration testing equipment has been acquired. A shaker system and a spectrum dynamic analyser system are also available.

Instrumentation and Control Laboratory

The major equipment in this laboratory includes a SCORBOT Robot, which is a vertically articulated robot with a five-degree-of-freedom mechanical arm. Projects using this robot can be programmed by two languages: SCORBASE (menu driven) and ACL or Advanced Control Language. Other facilities include a high-precision TESTOTERM measuring instrument for velocity, temperature, humidity and pressure measurement, the Honeywell PID Process Control Model Plant, which is a liquid level control rig used to demonstrate water level control, the FEBACK Electro-hydraulic Servomechanism, which is used to investigate the effects of load changes in open and closed loop velocity, and a three-dimensional laser digitizer for non-contact precision measurement.

Automation and Robotics Laboratory

The laboratory facilities include a SEIKO four-axis, closed-loop DC servo robot, a Micro-In Circuit Emulator (MICE) which can emulate most of the industry-standard microprocessors, an Arium Logic Analyzer for debugging and trouble shooting , a CFG Vision System for image capturing and memory storage, a PCB precision multi-function workstation for custom design and solutions of limited PCB prototypes and a LADAR three-dimensional laser scanner system for surveying static three-dimensional profiles.

Metrology Laboratory

The laboratory is equipped to provide precision measurement capabilities to the other laboratories. The major equipment include a CNC co-ordinate measuring machine for linear measurement, a FORMTALLYSURF and TALLYROND devices for round and square measurements, profile projectors and some toolmaker's microscopes.

Graphics Laboratory

The graphics laboratory is principally geared to provide facilities to train the large number of first-year engineering students, which numbers in excess of 1000 students. There are a total of 47 DECstation 5000/125 and 5000/240 workstations with two- and three-dimensional modelling, solid modelling and surface software.

The CAD/CAM laboratory

The laboratory has been set up to support both undergraduate and research work. It is well equipped with 27 PC486s, 20 VAXstation 3100 and 3200s, and five DECstation 5000/125s. Software available includes Algor FEM/ FEA, Pafec FEM/FEA, MARC FEM/FEA and various CAD packages compatible with the PCs.

The CNC Laboratory

The laboratory has been equipped with several advanced machine centres for both undergraduate and research support. These include a Toshiba four-axis horizontal machine centre, an Agie EDM die-sinking and wire cutting machine, a Hamai vertical machining centre, a Ikegai turning centre, a Maho universal CNC milling machine, a Zoller tool presetter and a Leblond Makino vertical machine centre.

Workshops

There are two workshops which provide basic support facilities for the other laboratories in machining, cutting, joining, sheet metal pressing, woodworking, extrusion and heavy pressing. The major floor space of the workshop is occupied by 16 units each of lathe and milling machines for hands-on training by undergraduates. Another major facility is the welding section, which comprises eight gas weld units, nine arc weld units and one unit each of plastic welding, MIG and TIG. All these have been used for hands-on undergraduate projects.

APPENDIX C: DETAILED LIST OF EEE LABORATORIES

Power System and Electrical Machines Laboratories

The laboratories focus their teaching and research facilities in the areas of planning and analysis of new power systems, computer control and operation using advanced energy management system (EMS) concepts, development and implementation of advanced strategies for the monitoring, protection and stabilization of power systems, energy technology, electrical machines, power electronics and drive systems.

Electronics Laboratories The laboratories are equipped with a comprehensive range of equipment, including test instruments and computing facilities with various application softwares to support student projects in the design and development of electronic circuits and systems.

PCB Laboratory

This laboratory comprises the dark rooms, a yellow room and the through-hole etching room. The dark rooms include a negative film development room and the camera room. The yellow room consists of a laminator room and exposure and resist development room. It is equipped with a complete range of equipment for fabricating double-sided through-hole printed circuit boards (PCBs or PWBs). It is used to support the second-year teaching, make prototype boards for industrial attachment (IA) and final year projects.

Microprocessor Centre

This laboratory is set up to support the teaching and research in the area of microprocessor-based systems design. The centralized facilities in this laboratory consist mainly of the Hewlett Packard HP6400-UX Universal Multi-user Development System which can support up to 32 simultaneous users for software/hardware development. It consists of four sub-host systems (based on the HP9000 series 300 computers) linked to a central file-server through an Ethernet link. Five older HP64000 stand-alone stations are similarly linked to optimize the resources of the Centre. The microprocessors which are currently supported include the Intel 8085, 8086/8087, 8051, 8088, 80286, the Motorola 6800, 6809, 6805, 68000, 68020, Zilog Z80, Z8001, Texas Instruments TMS 32010, and AMD bit-slice processors.

CAD/CAM and IC Design Laboratories

The laboratories are equipped primarily with Mentor Graphics EDA software running on Sun SPARCstation 10 workstations and related peripherals. They are used to support the teaching and research activities in the design of VLSI circuits and systems. Teaching sessions include logic and circuit simulations and full custom digital and analogue VLSI design. Research activities include high-level and logic synthesis, semiconductor device modelling and simulation using Monte Carlo techniques and current-mode circuit design, among others. The laboratories are also capable of performing basic failure analysis on IC chips such as decapping, photographing, ESD testing and device characterization.

Characterization Laboratory

As part of the focus of the School of EEE in R&D activities in microelectronics, the Characterization Laboratory provides facilities and services to support characterization and measurements of advanced electronic materials such as GaAs, diamond thin/thick films and VLSI systems. The major analytical instruments available in the laboratory include a photoluminescence system, an X-ray diffractometry system, a Raman spectrometer, a scanning electron microscope and an electron beam probe system. These systems together provide a fairly extensive range of analytical capabilities for the investigation of various electronic, physical and molecular structural properties of electronic materials prepared in the Clean Room. In addition, the electron beam probe system supports design verification, fault localization and device characterization of VLSI circuits.

Hybrid Microcircuits Laboratory

The Hybrid Microcircuits Laboratory has the infrastructure of plant and equipment to support teaching and postgraduate research in the field of thick/thin film hybrid technology. State-of-the-art fiber-optic circuits, D/A converters and automobile hybrids have been developed and fabricated successfully. The laboratory is equipped with the following instruments: sputtering system, mask aligner/exposure unit, pick and place system, reflow soldering furnace, laser trimmer, die bonder, wire bonder, thick film writer and thick film surface scanner.

Computing Laboratory

This laboratory provides facilities for teaching and research in the areas of electronic CAD/CAM and artificial intelligence. The laboratory supports software-related teaching, research and development. It also acts as a terminal room in the School for the NTU's VAX computer system and the School's MicroVAX computer. Fifty-nine ALR386 PCs linked to the NTU's VAX computer system and eight PCs linked to the School's MicroVAX computer form the basic equipment for functioning as a terminal room. Equipment for CAD/CAM and SPICE experiments include four Apollo workstations, 15 Abacus AT computers, one magnetic tape drive, two DSP 80A servers, three Calcomp plotters and three printers. The activities held in the laboratory are second-year projects on numerical analysis, second-year experiments on PCB design and circuit simulation, second-year in-house practical training projects, the final-year design course on computer engineering, final-year and research projects on software design and development.

Computer Engineering Laboratory

This laboratory provides facilities and support for second-year in-house practical training projects, third-year experiments on 80286 microprocessor development and assembly language programming, the third-year project on microprocessor controlled systems and final-year projects on microprocessor and PC hardware. Facilities include 80286 microprocessor training kits, 80286 motherboards, EPROM programmers, UV EPROM erasers, 80286 emulators, etc.

Centre for Signal Processing

This has been established in the School to promote and lead R&D activities in the fast growing field of signal processing. Although signal processing has all along been an area of excellence in the School, the formation of the CSP intensifies and focuses these research activities. At present, the CSP has about 50 members, comprising academic staff, research fellows and postgraduate students. It has identified five areas of interest as the focus of its activities: speech processing, image processing, adaptive signal processing and mathematical techniques, neural networks and parallel processing, and applications of signal processing hardware. The CSP has also formulated broad action plans to promote and lead in its activities, namely (i) to keep abreast with the latest developments in the general area of signal processing, (ii) to conduct R&D work in specific areas of interest, (iii) to develop R&D projects with industries, (iv) to provide training programs, technical advices, feasibility studies and consultancy services in signal processing related problems, and (v) to run seminar series and continuing education courses in signal processing areas.

With the continuing support of the NTU and the active participation of staff members, the CSP will become a centre of excellence both locally and internationally in the near future.

Instrumentation and System Engineering Laboratory

Teaching and research in process control and instrumentation are the main activities of this laboratory. Major facilities include a Foxboro intelligent automation series workstation, a chlorine injection control system simulator, a process simulator and an expert self-tuning PID controller. Also available are a process control calibrator, test instruments, DC servomechanisms, an analogue computer and many PCs for third-year and final-year students.

Control Engineering Laboratory

The main activities of the laboratory are to support second-, third- and final-year students in design and project work in control engineering, advanced control systems, industrial automation and instrumentation, biomedical engineering and consumer electronics. Some major equipment in the laboratory includes data acquisition systems, digital signal analysers, programmable logic controllers, control simulation software (ADVOCET, FILTERS, LSAP, SIMMON), ICE 5100 emulation software and biopotential signal generators and measuring equipment.

Avionics Laboratory

The objective of the Avionics Laboratory is to provide teaching and research facilities for final-year projects, Ph.D./M.Sc. projects, and staff R&D projects. Existing equipment includes an HP 8791 frequency agile signal simulator and an HP 85638 spectral analyser. Additional equipment, including a flight simulation workstation, airborne radar image processing hardware, navigation sensors (gyroscopes and accelerometers) and associated electronics, will be installed along with simulation software for flight control, radar performance and inertial navigation analysis.

Research Laboratories

Four research laboratories have been established to support R&D work in the preferred areas selected by faculty members of the School. Activities are focused on power system simulation, SCADA, power electronics and machines, acoustics research, computer graphics, artificial intelligence, parallel processing, networking and data communication, robotics, computer vision, computer control and automation.

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