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A Mechatronic Engineering Curriculum for Professional Education*

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This paper deals with a mechatronic engineering curriculum that is suitable for professional education at the degree level, which has been recently developed and implemented at the City Polytechnic of Hong Kong. The curriculum places emphasis on consumer mechatronic product design and process mechatronics.

THE NATURE OF MECHATRONIC ENGINEERING

THE SUBJECT field of machine systems, ranging from consumer products to complex machinery, is experiencing a far-reaching revolution concerning their technological make-up. Until 50 years ago, machinery was almost entirely mechanical in nature. While accepting the presence of electric motors as the prime movers, control systems and displays were also mechanical in nature, frequently using ingenious mechanisms to achieve the desired results [1]. However, the increasing use of electronics in industrial control systems—greatly accelerated by the introduction of transistors in the 1950s—the advent of fast, reliable electronic digital computers in the 1960s and 1970s, and the recent widespread availability of semiconductor chips that can be configured to suit the specific application in hand (i.e. ASICs—application-specific integrated circuits) have caused machine and product design to become highly multidisciplinary in nature [1, 2]. Thus, mechanical engineering has combined with electronics and computer control in a closely integrated way to conceive and develop products and processes that would not have been possible without such a multidisciplinary approach. The term coined for this approach to engineering design is 'mechatronics' [1–3], which is of extremely recent origin, having been coined no more than 12 years ago by the Japanese Ministry for Trade and Industry (MITI). Although several definitions have been adopted to describe mechatronics, the one used by the Industrial Research and Development Advisory Committee (IRDAC) of the European Community seems to be the most appropriate:

> A synergistic combination of precision mechanical engineering, electronic control and systems thinking in the design of products and manufacturing processes.

Common to all mechatronic products/systems is the strong interaction of all the disciplines involved, in the design as well as the production phases. With a mechatronic design, products can be realized which, in each of the disciplines alone, may be difficult or even impossible to realize [1]. The result is a product with superior design specifications and, hence, with greater value added. It is therefore useful to appreciate what is involved in the design of such products to understand the technical scope of mechatronic engineering. Neither the mechanical nor the electronic engineer is capable of migrating from the classical to the modern on his/her own. Such a migration requires the interdisciplinary expertise of 'mechatronics'. 'Mechatronic design engineering' refers to the design of products involving mechatronic strategies, i.e. those exploiting the synergistic combination of mechanical, electronic and computer engineering.

Figure 1 shows the further expansion of the disciplines involved as a result of the addition of the term 'design' [4, 5] to 'mechatronic engineering'. Thus, in addition to mechanical, electronic and software engineering, mechatronic design engineering involves the consideration of aspects related to industrial design, manufacturing engineering and marketing.

From the industrial viewpoint, as shown in Fig. 2, mechatronics engineering can be divided into two broad areas:

- *product mechatronics*—i.e. the design of mechatronic products; and
- *process mechatronics*—i.e. the utilization, operation and maintenance of mechatronic process machinery, mainly in the manufacturing industry.

Product mechatronics could be further subdivided into:

- *consumer products*—which tend to be mass produced, have shorter lifecycles, and have

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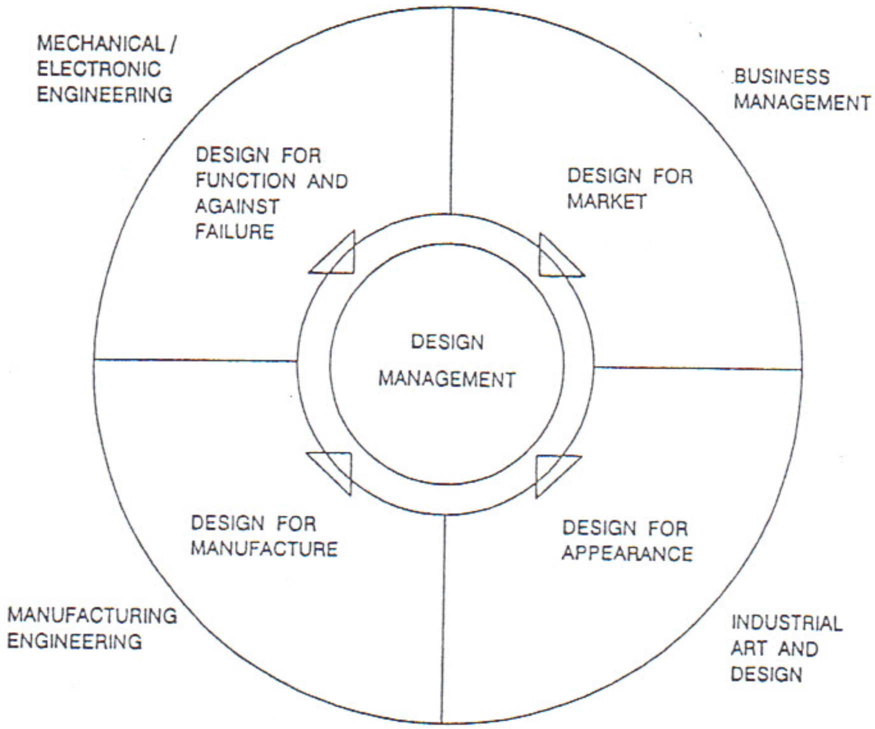

Fig. 1. The interdisciplinary nature of design and the role of design management [4]

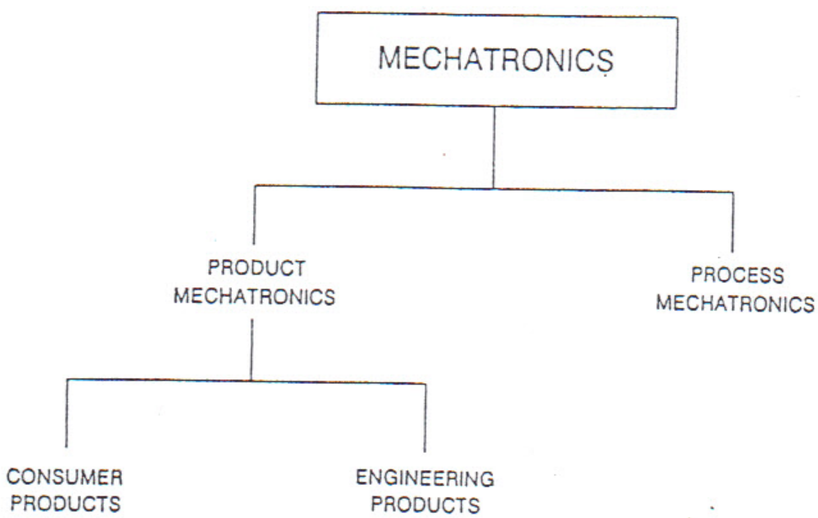

Fig. 2. The scope of mechatronics.

greater pressures on cost, and greater requirements in terms of aesthetics; and
- *engineering products*—which tend to be technically much more complex.

Educational developments so far in the West and Japan [2, 6] have concentrated on the needs of mechatronic engineers involved in engineering products and process mechatronics (in that order). However, from a pedagogic point of view, the knowledge elements required for both these sectors overlap substantially. Furthermore, the design of consumer products involves many other aspects. Thus, the needs of consumer product mechatronics have not yet been significantly addressed in the West and Japan. However, from the viewpoint of Hong Kong [7, 8], the primary need for mechatronics is in the context of consumer products and manufacturing processes. Mechatronic engineering in Hong Kong thus has to grapple with an underexplored dimension of mechatronics, i.e. consumer product mechatronics.

CURRICULUM DESIGN PRINCIPLES

The curriculum is developed with the aim of producing mechatronic engineers who are capable of integrating the diverse disciplines of mechanical, electronic and computer engineering with a view to:

1. designing and developing high value added discrete products of a mechatronic nature; and
2. implementing the engineering aspects related to utilization, operation and maintenance of flexible manufacturing equipment.

To meet this aim, the following principles have been employed in the design of the curriculum:

- Direct the curriculum mainly towards meeting the needs of consumer mechatronic product design and process mechatronics related to the manufacturing industry.
- Recognize that design
  - is a complex and open-ended activity requiring the refinement of creativity and experience through application;
  - is often a group activity in industrial practice;
  - is a combination of art and science;
  - requires a broad overview of market needs, business goals and currently available manufacturing technology.
- Emphasize the interdisciplinary approach as far as possible.
- Develop the mechanical and electronic design aspects systematically, while providing a broad understanding of computers to enable their effective utilization in design.
- Recognize that control engineering (especially motion control) is a core activity.
- Develop a broad understanding of the interactions between design, manufacturing and design management.
- Take advantage of computer-aided design and analysis software in order to enable the students to undertake more substantial design tasks.
- Develop the skills in technical communication that are required by all engineers.

COURSE STRUCTURE AND CURRICULUM

The course is divided into three years of study in the full-time mode for A-level graduates. Figure 3 shows the curriculum requirements ideal for a mechatronic engineering course in terms of nine module groups or themes. Figure 4 shows the sequencing of and the interactions between the different module groups in the course; the principal content of each of the groups is presented below.

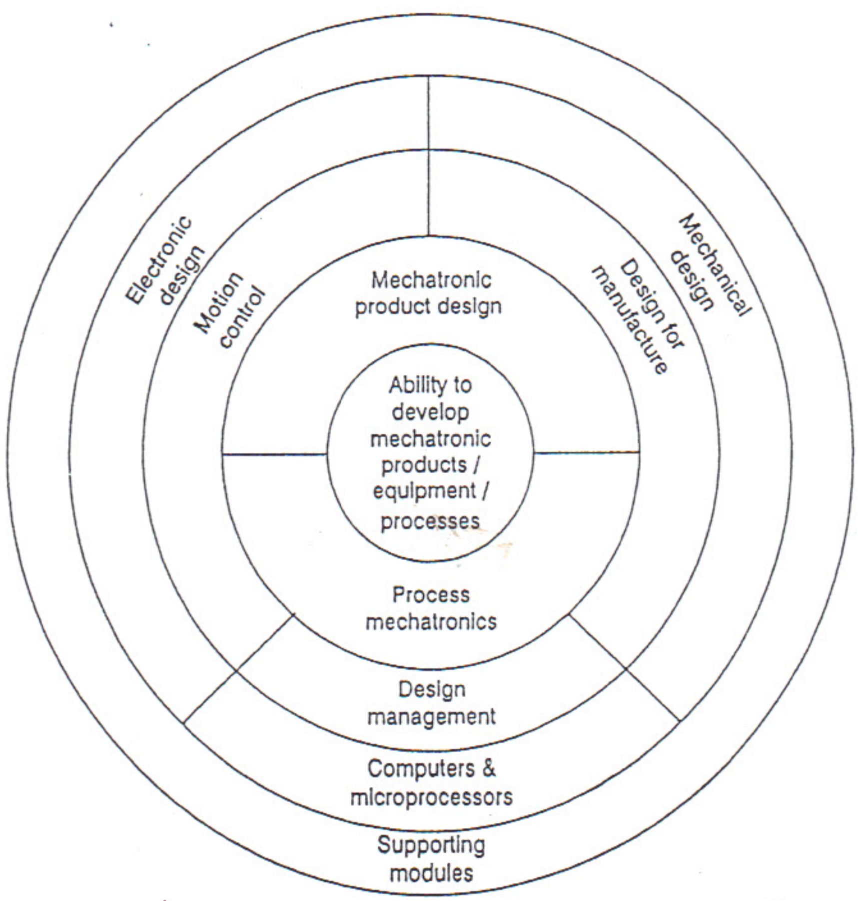

Fig. 3. Curriculum requirements ideal for mechatronic engineering education.

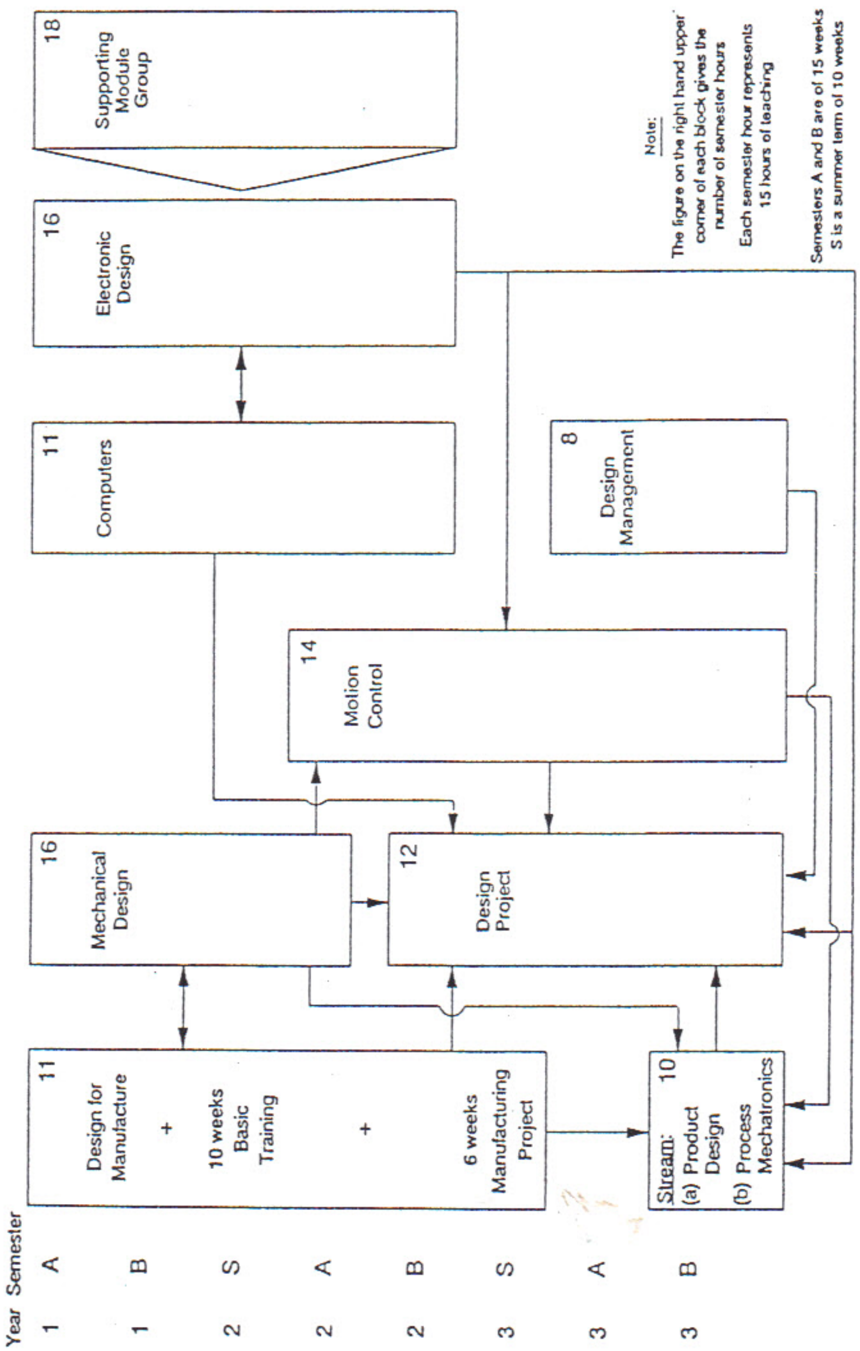

Fig. 4. Interactions between the various module groups/themes.

The mechanical design theme

This theme, consisting of modules totaling 240 hours, extends over years 1 and 2. The aim of the theme is to provide a fundamental understanding of the principles underlying mechanical design and the skills necessary in their application.

The theme begins with the modules on 'Engineering Analysis and Design', which take 135 hours of study, and aim to equip the students with an understanding of the basic principles underlying the mechanics of materials and machines and provide opportunities for their application in the analysis of practical designs. A tutorial activity of 30 hours and a laboratory work of 60 hours is included, and the laboratory time is divided between regular laboratory exercises and a student-centred activity (SCA) project.

In the SCA, the students are divided into groups and asked to conduct a thorough analysis of a realistic mechanical design of a product or a machine subsystem. The students are expected to apply the principles learnt in the lecture sessions in order to analyse the kinematics, kinetics, dynamics, loading and stress analysis aspects involved in the practical design. Wherever appropriate, the students will be encouraged to refine the design on the basis of their analytical results. In addition, regular laboratory time is utilized for a series of analytical assignments and structured experiments related to the kinematics, kinetics, dynamics and stress analysis of machines and components.

The study of the mechanical design theme continues through two other modules, 'Heat and Fluid Flow' and 'Mechanical Design', lasting 30 and 75 hours respectively.

The module 'Heat and Fluid Flow' aims to provide a fundamental understanding of heat transfer and the flow of liquids and gases under isothermal conditions. The 'Mechanical Design' module aims to provide a practical appreciation of the mechanical design process through the study of selected topics and design case studies under the supervision of the teacher. The topics covered include design standards, an awareness of the commercially available mechanical elements, subassemblies and joining techniques. In addition, the module covers two major topics: mechanisms design and thermal design. Mechanism design aims to develop a fundamental understanding of the analysis and synthesis of mechanisms in order to support subsequent studies in motion control and consumer product design. In addition, the study of the thermal aspects involved in mechanical design is undertaken.

The electronic design theme

This theme, of 240 hours duration, extends across years 1 and 2. The study of the theme begins with 'Basic Electronic Engineering', which takes up 120 hours in year 1. The students are first equipped with a basic understanding of electrical circuits, electric motors and systems. The students then proceed to study the basic principles of analogue and digital electronic circuits, devices and systems. Laboratory and tutorial support of 30 hours each is included.

The study of the electronic design theme continues in year 2 with 'Instrumentation Design', which lasts for 120 hours. Here, the students study the fundamentals of memory devices and structures, and the design techniques involved in sequential circuits and digital controllers, and obtain an understanding of the principles concerning amplifiers, design of operational amplifiers and filters, transducers, signal transmission and instrumentation systems in the context of mechatronic products. Laboratory and tutorial support of 60 hours is included in the modules along with a SCA.

The computers theme

This theme, of 165 hours duration, aims to develop a fundamental understanding of the principles of programming, data structures, the structure of computer hardware, software engineering, communications and databases which are essential in the design of mechatronic products and utilizing mechatronic manufacturing equipment. The theme starts with 'Software and Data Organization', where students are provided with a basic understanding of the structure and syntax of programming languages and opportunities for developing programming skills using a structured language.

The study of computer software is extended down to the level of assembly language programming in 'Microprocessor Interfacing and Computer Organization'. Further, in this module, the students study how microprocessors could be interfaced with external devices and integrate into a functioning computer-controlled system. Laboratory and tutorial supports of 15 hours each are provided for this phase of study. In 'Embedded Systems Software Engineering' students learn the essential techniques for developing software for embedded systems, including the design, development and maintenance of software. Laboratory support of 15 hours is included in this module. Finally, in 'Manufacturing Communications and Databases', the students study contemporary strategies in networked communications and distributed databases in manufacturing shops.

The design for manufacture theme

This theme consists of academic modules of 165 hours, 10 weeks of 'Basic Training' (340 hours) and a 6 week 'Manufacturing Project' (210 hours) in an industrial centre. The study of the theme begins with 'Introduction to Manufacturing Processes', where the students are equipped with a basic understanding of the principles of operation and capabilities of the common range of manufacturing processes.

In 'Basic Training', taken in the summer of year 2, students gain an understanding of the wide range of manufacturing processes, equipment and tooling utilized in the manufacture of mechanical and electronic products in a simulated industrial environment. The learning mode is essentially hands-on operation of processing equipment in order to develop practical skills. During the 10 weeks of training in the industrial centre, students also spend 60 hours on 'Engineering Drawing', where they refine their technical communication skills using the drawing-board and simple computer-aided drafting techniques. The emphasis here is on three-dimensional visualization using sketches in the context of mechanical elements. A basic understanding of tolerancing and manufacturing drawings is also provided.

Following the 'Basic Training', students study the principles of computer-aided design/manufacture (CAD/CAM), computer numerical control and the associated NC programming techniques in 'Design for Manufacture' (120 hours). In addition, the broad understanding of classical and modern manufacturing technologies so acquired is directed towards the development of an understanding of how mechanical products could be designed for ease of manufacture. This is done by including topics that provide an in-depth study of the capabilities, manufacturing defects and how these could be rectified by prudent product design in the context of the common range of manufacturing processes including assembly. The emphasis here is on basic concepts and systematic design for manufacture.

The design for manufacture theme culminates in the 'Manufacturing Project', which lasts 6 weeks, that is undertaken in the summer term of year 3. The project, which is carried out in the industrial centre, aims to develop the skills required in the planning and execution of the manufacture of a fairly complex mechatronic product in a jobbing environment.

The students are divided into small groups and each group is provided with the full technical specifications of the product to be fabricated. The products are realistic in nature and are expected to be drawn from the industrial work being carried out by the industrial centre or the requirements of our department.

The product should contain both mechanical and electronic elements in order to suit the intention of this course. Whenever feasible, the students may engage in the fabrication of a product related to, or derived from, the design project work of their own or those completed in previous years. The students are expected to work in autonomous groups, plan their own work, study the manufacturing infrastructure available in the industrial centre and utilize it appropriately.

The motion control theme

Motion control is a core activity in mechatronic design. This theme, of 210 hours duration, aims to build on the expertise gained in the mechanical and electronic design themes by providing an in-depth understanding of the principles of control, the common range of control elements and their application in the development of mechatronic control systems with emphasis on motion control.

The study of this theme begins with the module 'Control Principles', where the students acquire an in-depth understanding of the static and dynamic behaviour of feedback control systems. While the emphasis in the lecture sessions here is on the fundamental principles of feedback control, practical appreciation of the common range of control devices is acquired through associated laboratory work of 30 hours duration. The syllabus covers the principles of linear control, utilizing both analogue and digital (computer-controlled) strategies.

The study of this theme continues in year 3 through the module 'Power Electronics and Drive Systems'. Here, students are provided with a fundamental as well as practical understanding of the design principles and techniques associated with power electronics and electrical servo motors. Laboratory and tutorial support of 15 hours each is included in this module.

The aim of the final module, 'Motion Control Design', in this theme is to integrate the principles of design concerning mechanism design, digital electronics, microprocessor, interfacing, software engineering, feedback control theory, power electronics, servo motor design, etc., studied in the previous modules with a view to designing mechatronic motion control systems. The emphasis here is on a practical approach. Topics covered here include sensors, human–machine interfaces, machine–machine interfaces, systems design methodology and a practical case study.

Practical realization of the aim of integration is achieved in the associated laboratory work of 30 hours duration, where the students are assigned a substantial motion control task as a SCA. The task shall be realistic in nature with specification derived from a real-life problem. Each student group will be provided with a specification of the motion control system needed. The students are expected to design, develop and test the system (at the bread-board level) within the constraint of the control hardware available in the laboratories. Tutorial support of 15 hours is also included in this module.

The design management theme

This theme, of 120 hours duration, is studied in year 3 in view of the need for students to be sufficiently mature in terms of design ability and group behaviour before they could effectively study the design process at a macro-level from a managerial pont of view. The 'Design Management' module aims to equip the students with a broad understanding of the corporate environment within which industrial design projects are undertaken. The focus is thus on the role of a design manager's relationship with the manufacturing and corporate environment. Further topics covered here include principles of organization and management, marketing and product liability. In addition, there are topics focusing on the activities within design management through a study of the methodology of managing a design team, value engineering, economic decision making, etc. The subsequent module, 'Product Quality and Reliability', covers topics such as tolerancing, quality control and design for quality, reliability, maintainability and testability.

The streams

Students can specialize in one of the two streams, namely product design and process mechatronics.

Subjects for the students of the product design stream are 'Mechatronic Product Design' and 'Computer-Aided Engineering'—a total of 150 hours of study. The aim of 'Mechatronic Product Design' is to provide an in-depth understanding of the professional aspects specific to the design of mechatronic products that have not been studied earlier in the course. Topics covered here include ergonomics in design, product safety and the testing of products against adverse mechanical and electrical environments. Forty-five laboratory hours are included in this module to provide laboratory/tutorial support for this phase of study. In 'Computer-Aided Engineering (CAE)' the students are provided with an in-depth understanding of the modelling, data structure and algorithmic issues underlying the computer-aided design, analysis and simulation of electronic and mechanical subsystems. Such an understanding of CAE is believed to be highly useful in organizing modern design offices in the industry. Extensive use of CAE is believed to be essential in meeting the ever-shortening design lead times and in the context of the extremely broad technical scope of mechatronic design.

Students belonging to the process mechatronics stream spend a total of 150 hours on 'Mechatronics Production Equipment' and 'Flexible Manufacturing Systems' modules. The aim of this stream is to provide the knowledge and skills necessary in the utilization and maintenance of processing equipment, which is becoming increasingly mechatronic and sophisticated. In 'Mechatronics Production Equipment', students are provided with a practical understanding of the control structure and technical complexity of flexibly automated production equipment such as CNC (computer numerical control) machines, robots, AGVs (automated guided vehicles), programmable conveyors, etc. In 'Flexible Manufacturing Systems', students study flexible automation technology from a systems point of view. The emphasis here is on how to integrate CAD, CAM, database management, data acquisition, networking, etc., into a functioning system. Forty-five laboratory hours are assigned to this module to provide the necessary support in terms of laboratory and tutorial work.

The supporting module group

This group, of 270 hours duration, aims to support other modules in the course through the development of the understanding of the necessary topics in engineering materials, mathematics, technical communication skills in English and an awareness of the relationship between manufacturing and society. The 'Engineering Materials' module is designed to equip the students with a basic understanding of the properties of engineering materials such as metals, steels and ceramics, their failure mechanisms and applications in manufacturing and design. As a part of the practical assignments provided here, the students analyse the material requirements for the various components of the mechanical design/analysis exercise undertaken, in parallel, in engineering analysis and design. Laboratory support of 30 hours is included in the module.

Ninety hours of study is directed towards 'Engineering Mathematics'. The topics covered here include differential calculus, ordinary and partial differential equations, complex variables, vectors and matrices, statistics and numerical analysis. A thorough understanding of these topics is essential for providing the necessary theoretical background for the analytical subjects in the mechanical design, electronic design, motion control themes and in CAE.

'Technical Communication for Engineers' introduces the basic language and communication skills necessary in listening, writing, discussing and technical reporting. The teaching in these modules is done in small groups utilizing a multimedia learning environment.

A module on 'Manufacturing and Society' gives a historical overview of the evolution and social implications of manufacturing. Also, organizational aspects of and the challenges faced by manufacturing in society are covered as a part of students' civic education.

The design project

'Design Project I/II', which has been assigned a total of 180 hours, aims to refine the creative, analytical, applicational and integration skills of students through the planning and execution of a substantial design task. To this end, the students are subdivided into small groups, with each being assigned a design task. Efforts are made to derive the task from real life through appropriate industrial support. The project extends over year 2 ('Design Project I') and year 3 ('Design Project II') in order to enable the students to refine their creative skills at a relaxed pace and progressively assimilate the diverse design concepts being studied in other modules.

The design objective for each group is assigned at the beginning of the first design project module. By the end of 'Design Project I', students are expected to have understood the functional objectives of the product to be designed, the technical/economic requirements it must satisfy, and come up with a set of feasible alternatives for design strategy, select the 'best' alternative, subdivide the product into subsystems, identify the requirements of each subsystem and allocate the work appropriately amongst the group members. Group work during 'Design Project I' should help develop the skills needed in group interaction.

Each student works independently on the design subtasks allocated to him/her in 'Design Project II', while continuing to interact with other members in the group in order to ensure compatibility. The aim is to produce and test a prototype at the bread-board level. Finally, each group is expected to make a presentation on their achievement at the end of 'Design Project II'. The assessment of the project work will be based on the extent of achievement, scientific basis, intellectual depth and creativity, on an individual basis.

SUMMARY

A mechatronic engineering curriculum with an emphasis on consumer mechatronic product design and process mechatronics has been presented. The entire syllabus is divided into nine subject groups/themes that are properly balanced and integrated. In keeping with the special requirements of the study of design a significant proportion of the course is devoted to 'active learning' through 'doing' as opposed to 'passive learning' through attending lecture sessions. Thus some 60% of the total contact time in the curriculum is devoted to laboratory, project, tutorial and training components, where the student is largely in the active learning mode. The course has 405 laboratory hours and 180 hours of design project work, where students undertake a mixture of structured experiments, student-centred activities centred around practical mini-projects, and a major design project. Much of the activity is done in groups, thus simulating the team environment in which design projects are typically executed in industry.

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