Introduction to Mechatronics: A Graduate Engineering Course

Dr. Sohail M. Qureshi
Department of Avionics Engineering, College of Aeronautical Engineering
PAF Academy Risalpur, Pakistan

Abstract

Mechatronics is the junction where concepts from various domains such as mechanical engineering, electrical engineering, and computer science are merged to design, build and operate products. In recent years, the need for mechatronics education has gained much popularity primarily by virtue of the high demand for reliable and cost effective products. This paper presents a three-credit graduate-level course that has been developed to impart interdisciplinary education to professional engineers who work across the boundaries of various disciplines. The course is being offered at College of Aeronautical Engineering, Pakistan as a requirement for the graduate students enrolled in the program for Masters in Avionics Engineering. The paper addresses major ingredients of the course syllabus and design exercises. The multidisciplinary design exercises are used to pose real life design environment through emphasizing team work. The lecture material is applied in the exercise scenario to design and develop test products.

Introduction

The shrinking global market has resulted in increasing pressures upon companies to make cheaper and more efficient products. As a consequence, there is an increasing demand for research in the areas such as design and manufacturing of products. The scenario has generated much interest in the subject of Mechatronics which has been under discussion for many years and is gaining popularity. *Mechatronics* has been defined by many researchers in various ways. For example, ACAR defines Mechatronics as the synergetic combination of various disciplines thinking in the design of products and processes [ACAR 1997]. Hanson defines Mechatronics as mechanical systems programmable with perception, action and communication [Hanson 1994]. Mechatronics has also been defined as totality of fundamentals and techniques in a unified framework for service and production of future-oriented machines. The author tends to agree with Rizzoni who opines that Mechatronics is a philosophy of design that has surfaced because of the extensive use of microelectronics in engineering products and processes [Rizzoni 1997]. The Mechatronic design, henceforth, requires an integrated approach to encompass various fundamental engineering disciplines. Apart from the definition of Mechatronics, it is very clear that the final consequence of Mechatronics education is aimed at improving the design of Mechatronic products. According to Burr [Burr 1989], the most successful companies emphasize on four areas related Mechatronic design: fast reaction to changes in competition, shorten product cycle, competitive product properties, careful planning for new markets. To keep such competitive edge, therefore, the companies need graduates that understand how to integrate traditional design methods with core technologies such as mechanical and electrical engineering.

The Mechatronics coursework, in view of the author, must include ingredients that are deemed important in the design process of Mechatronic products. The understanding of the process of Mechatronic design, henceforth, becomes of prime importance in a course of Mechatronic education. Also, the fact that Mechatronics is aimed at imparting applied education, the coursework has to be tailored to the needs and background of the students involved. The coursework presented in this paper was developed for the graduate students of Avionics engineering as a core course for their masters degree program. There are various components of Mechatronic education that are very important but were not included in the course so as to avoid overloading of the students in one course of the semester.

Background

As mentioned earlier, the author is of the opinion that in order to impart effective education in Mechatronics, the design process of Mechatronic product design must be understood first. Such understanding provides the basic foundations that need to be used to focus the curriculum of Mechatronics education. Although, much work has been done in the area of traditional design process and product development [Pahl 1993], there are no available formalised models of Mechatronic design process. The following text is intended to provide some insight of the Mechatronic design process and its major elements as deduced from literature and real design scenario.

A typical Mechatronic design process as shown in figure 1, is similar to any other traditional product design and starts with the client or market analysis. Particularly true for Mechatronic products, satisfaction of the client (or the market) is the major driving factor in the design process. The client dialogue, therefore, is normally an integrated forum including a team of designers, a team leader, and representatives from various other functions such as finance, sales etc.. The client dialogue generates a mission statement narrating the needs of the client. The product specifications are then developed from these needs and a traditional design process starts. In the design of Mechatronic products, however, the design constraints on one domain may actually be a function of design decisions/constraints of another domain. For example, the design of structural components is constrained by the weight and size of the actuators which in turn may be constrained by the data acquisition technology. These integrated constraints and their solutions are a function of the background of various designers involved, and the extent to which design decisions are communicated from one another. At present there is no formalism associated with such a process and information is communicated very informally and in an unstructured manner. The issues involved in formalising such information is beyond the scope of this paper and the reader is referred to [Qureshi[1] 1997]. However, the point understood is that the Mechatronic design process involves extensive communication and management of information and personnel both.

Keeping in view the characteristics of a typical Mechatronic design scenario, the following knowledge components are considered important. The members of a Mechatronic design team need to have background knowledge in these components to contribute more effectively towards the product design.

- Design Theory: Because of the complex nature of modern technology and the pressures for the development of satisficing products, the design process needs to be very carefully planned and attention paid to every phase of design. There are various design methods that have been developed over time to aid each phase of the design process. Clearly, for a systematic engineering design, these design methods need to be taught to the students of Mechatronic education.
- Project management: Project management is the activity of planning and co-ordinating resources and tasks to achieve high quality, low-cost products while using minimum resources and time [Ulrich 1995]. For all but very simple products, the product development involves many people completing many different tasks. The integrated design of Mechatronic products, therefore, requires good understanding of project management techniques.
- Group dynamics: The Mechatronic design involves extensive interaction amongst the design team members. In a typical design scenario, the design team invariably comprises of members from many cultural and ethnic background. For the good health of the project, therefore, it is imperative that the group members are taught proven methods of group dynamics and concepts from research in this area. The students taking the course presented in this paper, however, are limited to a single environment and background. This module is, henceforth, paid no attention in the subject coursework.
- Communication of Information: In a typical design scenario, the members of a design team are separated by time and distance [Qureshi[2] 1997]. The learning of how to establish effective communication across time and space is of paramount importance in such design scenarios. It has been established that the traditional approach of documenting designs is not enough in today's competitive market. Amongst many other advantages such as design reuse, the effective storage of design information provides the kind of communication that is needed by today's design teams. It includes areas such as verbal communication, report writing, product and process modelling, and design history databases.
- Microprocessors: The microprocessors have found their way into every product design and are included in almost all Mechatronic products today. The Mechatronic students, therefore, need to understand the behaviour and structure of these logic devices. The study of microprocessors requires background knowledge in logic design principles, electronics, and programming.
- Materials: The design of Mechatronics products involves mechanics and mechanism

designs that include selection of material and failure analysis of the design. The curriculum of Mechatronic education, therefore, needs to include material that covers material mechanics and failure analysis of various mechanical designs. The level of detail taught in this component of Mechatronic education depends upon the background of the students and , obviously, upon the future pursuit of the student.

- Motion: The Mechatronic product invariably involve motion of one or more components. This motion is controlled through the microprocessor. For effective control, the processor has to have information about the position of the component and also its characteristics while in motion. Such an exercise involves understanding of the kinematics and dynamics of a system in motion. The field of robotics contains mature concepts that are very handy in such calculations. Also, robotics can be used for trajectory planning and execution of a mobile system. It is, therefore, necessary that robotics must be taught to Mechatronic students.
- Controls: The Mechatronic components in motion involve effective control of these components. Control theory and methods enter into Mechatronic design as controlled motion of individual actuators and the end effector is needed. The actuators are normally controlled through feedback control systems while the end effector involves optimal control. The students of Mechatronics, therefore, need to have understanding of control theory to utilise concepts such as disturbances, instabilities and error control. The non linear controls, though very helpful, are not considered necessary in basic courses of Mechatronic education.
- Computers: This is another important aspect of Mechatronic education where desktop/laptop computers can be used to develop programs and real time testing carried out. The program scan later be burnt on the programmable memories to work with the processor that is onboard the developed system. The students need to learn Assembly language to program for the microprocessor and also have understanding of how various components are connected to function together. Also, the simulations done in various other parts of the Mechatronic education need to interoperate seamlessly. At present, no such software is known that can transport the results of say MATLAB directly into Assembly programs. Students interested in software development may pursue this avenue. Another venue in this regard is databases concerned with storage and retrieval of design information which consumes up to 50% of design time [Allied 1995]. In the course presented here the students are expected to have understanding of Assembly language and hardware interfacing. The other areas, related to computers in Mechatronics, are beyond the scope of this course.
- Sensors and Instrumentation: All control of the Mechatronic system depends upon the ability to measure, communicate, interpret, and display the magnitude of the variable that needs to be controlled. There are two broad categories of sensors that are normally used in robotics: those that allow interaction with the world, and those that are used to control the robot itself [Stadler 1995]. The students may pursue this specialisation of data acquisition and sensing. Though an extremely important component of Mechatronic design, this course pays no emphasis on the subject of sensors and instrumentation.
- Electronic interfacing: The electronic interfacing requires appropriate conditioning of the information before it is fed to the corresponding module such as the control module, or the actuators. The data has to be made compatible with the system accepting it. Also, secure communication needs to be ensured when data is being transported. The students, along side of digital design, have to be made familiar with concepts such as interference and disturbance that may be generated due to wiring in very close proximity, inappropriate heat profile of the system etc. The electrical engineering students have experience with such elements of electronic devices and, therefore, no emphasis is given to this module.
- Actuators: The students of Mechatronic education must have clear understanding of issues involved in the selection and operation of various actuation mechanisms. The study of actuators, however, involves

basic understanding of hydraulics, pneumatics, and motors. The students here are electrical engineers with reasonably good background of motors and no understanding of hydraulics and pneumatics. This topic, therefore, is not included in the subject coursework.

Mechatronics Learning

There is an ongoing debate on whether specialist engineers are needed for Mechatronic design or generalised engineers with good interpersonal skills are sufficient. In one case there is more emphasis on specialised knowledge while the others require engineers who are very co-operative and provide a broad base for optimal design of products and processes. It is important to note that the Mechatronic coursework has invariably emphasised hands-on learning with reasonable emphasis upon the core corpus of knowledge. The aim of Mechatronic education, henceforth, had been to produce graduates who have a head start in the product development companies. The in house training, felt necessary by the companies, will be more fruitful to graduates who have been through a formalised Mechatronic coursework.

There are two basic philosophies that govern Mechatronic learning around the globe. In Japan, for example, most of the companies assume that design is learnt on the job and, therefore, conduct in house training programs focused at producing generalised engineers [ACAR 1997]. In the rest of the world, the industry is sponsoring university efforts to develop courses aimed at Mechatronic education. On the academic front, there are various universities that are offering full fledged programs in the field of Mechatronics. To name a few, Tohoku University of Japan runs a department with the name of 'Mechatronic and Precision Engineering'. The technical university of Denmark has Institute for Engineering Design, and Institute of Product Development that include research in Mechatronics [ACAR 1997]. In Europe many institutions are involved in Mechatronic learning to include University of Twente in Netherlands, Mechatronics group in Finland, Swiss Federal Institute of Technology, University of Linz in Austria, King's College London, Cranfield University and Lancaster University in England. The IMechE and IEE in UK have established a Mechatronics forum to advance this subject. In the United States, the institutions involved in Mechatronics learning include, but not limited to, Virginia Polytechnic Institute, Virginia Tech., Stanford University, Georgia Institute of Technology, Iowa State University, University of Delaware, Colorado State University, and Ohio State University.

Course Description

The graduate course presented here is a three credit course that is amongst the core course required to complete the Masters degree. The course is titled 'Introduction to Mechatronics' and is taught to professional engineers who have worked in the engineering profession for a few years. The focus of the course is to educate the students on the basic modules of Mechatronic design that have been presented in the previous section. As the students have an electrical engineering background, more emphasis is given to the subjects that are foreign to them while quick overviews are given for areas of their familiarity. All the course work will be limited to three hours per week but the consultation hours are not limited. Instead of providing labs, the students shall be given design tasks that need close collaboration with the industry and require routine working in the design labs. The objective is to provide a real design scenario where students can appreciate the little, non formalised, details that are involved in Mechatronic design. The course will be taught in the second semester of a lock step master program where they have already taken courses of digital signal processing and have been involved in extensive usage of tools such as MATLAB and at least one high level programming language. The prerequisites, however, include understanding of Assembly/C/C++, MATLAB, Microprocessors, digital design, applied linear algebra, and linear control systems. Due to the non-availability of cross compilers, the students will be asked to use ASSEMBLY language and the Microsoft Programmers' Workbench (PWB) to program for their design projects. The workbench includes an editor, compiler, linker, and a debugger to help students view the machine level manipulation performed by their programs. The course is decomposed into the following major modules:

Design Theory: The objective of this module is to provide the theoretical foundations that are necessary to understand the process of design. The module also introduces students to the various areas of research in engineering design. In particular, systematic approaches to engineering design are taught and students will be asked to use the same in the design project that will follow through the semester. The design task for this phase includes case studies or market analysis for a product design. The students will have the choice to conduct a case study on an existing problem in the industry or conduct a market analysis in the local market for a product. The final outcome of this exercise will be customer specifications for respective projects. The students will formulate technical design specifications that can be used to develop real products. Also, the students are taught various design methods such as Ö..Ö.. that have been developed by years of research to aid in the process of designing. In addition to other reference material, the text book used for this module is 'Engineering Design: A Systematic Approach' by J Pahl and W Beitz [Pahl 1993].

Project Management: The objective of this module is to educate the students on various tried out techniques of effective project management. In particular the focus is on project planning and project execution. The students will be taught various techniques of project planning such as design structure matrix, Gantt charts, and Pert charts. The project execution techniques include co-ordination mechanisms and project evaluation. The students are expected to make use of these techniques in the design project that has to be completed by the end of the semester. In addition to other reference material, the text book for this module is 'Product Design and Development' by Karl T. Ulrich and Steven D. Eppinger [Ulrich 1995].

Communication: The objective of this module is to teach students about efficient and effective means of communication. The student are given a short overview of the research in the area of product and process modelling, and design history systems [Qureshi 1998]. The students, however, are expected to use traditional documentation techniques and share information through informal means, formal project reports and presentations using multimedia software packages.

Microprocessors: The students being from electrical engineering curriculum are expected to have some understanding of the microprocessor. This module, however, is designed to provide a comprehensive revision of important concepts of the microprocessor. The Intel family of microprocessors is used for this module and students are expected to demonstrate their capabilities by using the microprocessor in their design project. The book used for this module is 'The Intel Microprocessors' by Barry B. Brey [Brey 1994]. Microsoft Programmers Workbench will be used to provide interactive learning of the microprocessor to the students.

Motion: The students have no previous background in the field of robotics. As this is one of the core areas of Mechatronics, much emphasis will be placed on teaching robotics to the students. Concepts of Forward and inverse kinematics, system dynamics, and trajectory planning will be taught in the course. The final design project will involve robotic manipulators and simulation of kinematics and dynamic behaviour of these mechanism. The text book used for this module is 'Analytic Robotics and Mechatronics' by Wolfram Stadler [Stadler 1995]. Mature algorithms will be used in MATLAB to model the behaviour of robotic manipulators used in the final design project. The demonstration of the modelled behaviour is done as the semester progresses.

Controls: The students are much familiar with the classical controls and a quick overview of the subject is considered sufficient. However, the students are expected to apply their control theory knowledge in the design project and demonstrate effectiveness of their implemented algorithm. The students will utilise MATLAB or a package of their choice to present control simulations of their design project. These simulations are also presented as the course progresses through the semester.

Materials: The students do not have any background in the area of material mechanics or structural analysis. This module is not aimed at providing proper education in such areas, rather, the idea is to provide an opportunity to the students to understand basis of the terminology that is commonly used in the mechanical domain of Mechatronic design. The topics include modes of failure, analysis of plane stress and strain theory of plates and failure theories. The students will be expected to utilise these basic concepts in their final design project. The reference book used will be 'Mechanics of Materials' by E. P. Popov [Popov 1978]. A visiting professor from Department of Aerospace engineering has been invited to deliver lectures on these fundamental topics of mechanical engineering.

Design Exercises

The design exercises are aimed at providing a real design environment to the students. The environment will be coupled with the classroom learning of new concepts in various areas. The design exercises provide hands-on experience to afford an ideal opportunity, to the students, for involving in design of real Mechatronic products. To keep the tempo of the course with the theoretical lectures, the design exercises are divided into various phases. The completion of a phase marks the progress made by the students and also acts as a milestone for the course. A presentation is made at the end of each phase to communicate the developments, made in that phase, to the rest of the class. The various design exercise phases are described below:

- Phase I: The design exercise in this phase focuses exclusively on the research methods that are taught in the classroom. For example, students will be asked to conduct market analysis through survey studies and interviews for the design and installation of a paper recycling plant. Another project includes the option of conducting control protocol study or market analysis for the design of a dryer machine for clothes.
- Phase II: The phase II marks the beginning of the final design exercise that is expected to generate a test product by the end of the semester. At this stage, the students have understanding of various design methods and project management techniques. The students are given a general idea of a particular Mechatronic a product. For the upcoming semester, a team of students will be asked to design and develop a globally fixed robot which is capable of carrying approximately 50 Kilograms of load. The robot will search for a ping pong ball in its limited workspace space, pick up the ball and throw it in a bucket that sits outside the boundary of the robot workspace. The students are expected to formalise the problem by developing a project proposal. The proposal will reflect clear understanding of the students as regards to various design methods and techniques for the problem definition. Also, the proposal provides a detailed project plan which utilises techniques taught in the classroom.
- Phase III: The phase III of the design exercise includes software development for the Kinematics analysis, Dynamic analysis, and calculation of the End effector position. The students will be encouraged to use MATLAB for generating numerical solution to the robotic analyses. In the same phase, the students will also develop control module for the robot. The control algorithm implemented, preferably, in MATLAB will provide the simulations of the robot control
- Phase IV: The phase IV of the design exercise includes developing the ASSEMBLY programs that are necessary for I/O and also communication across MATLAB and the Microsoft Programmer's Workbench. The completion of this phase is expected to demonstrate communication, of data and control signals, which is required for complete integration and operation of the final design.
- Phase V: This phase is aimed at hardware development of the final product design. The students are expected to utilise design methods taught in the class to develop conceptual design and bring out a final design. The structural design, selection of actuators, sensing, communication, and interfacing modules such as digital circuitry and motor controllers are all completed in this phase. This phase is completed when a manufactured robot with its supporting modules have been integrated.
- Phase VI: The last and final phase of the design exercise includes submission of final project report, a presentation of the project, and a fully functional model of the robot. The robot will be tested against the client specifications which were handed at the beginning of the project.

Conclusions

Mechatronics is a system level philosophy of design which aims for efficient integration of various components of a design process. Compared to the traditional approach of design, the learning of integrated problem solving approach is very difficult. In this paper we have presented some insight into some of the areas associated with the learning of Mechatronic design. The hands-on approach is provides the major thrust of the course and directs students to use the theoretical foundations learnt in the classroom lectures. Though, the course is being offered for the first time, it is expected to bring out many useful lessons that will be used to improve upon the contents of the course.

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