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Evolution of Mechatronics into a Graduate Degree Program in the United States: The NC State University Master of Science Program with Mechatronics Concentration*

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The evolution of mechatronics into a graduate degree program at North Carolina State University is described in detail. A curriculum has been developed which does not compromise academic depth, while providing the necessary breadth for a mechatronics degree. The curriculum is based on existing courses with a mechanism for continuous evolution towards an ideal mechatronics program. The master's thesis has a unique requirement that it should have members from at least two of the constituent areas to ensure the interdisciplinary nature of the program. Finally, the 'hands-on' aspect of mechatronics is emphasized through the requirement of a mechatronics design course.

INTRODUCTION

MECHATRONICS is the synergistic integration of precision mechanical engineering, electronics, computational hardware and software in the design of products and processes. Mechatronics, the term coined in Japan in the 1970s, has evolved to symbolize what mechanical design engineers do today worldwide. The revolutionary introduction of the microprocessor (or microcontroller) in the early 1980s and the ever-increasing performance/cost ratio has changed the paradigm of mechanical design forever, and has broadened the original definition of mechatronics to include intelligent control and autonomous decision-making. Today, an increasing number of new products is being developed at the intersection between traditional disciplines of engineering, and computer and material sciences. New developments in these traditional disciplines are being absorbed into mechatronics design at an ever-increasing pace. Thus, mechatronics has emerged as a legitimate multi-technological discipline that integrates several engineering fields including mechanical engineering, electrical engineering, computer engineering and information sciences. Driven by the need for improved design and production methods as well as the emergence of new information technology tools, mechatronics provides a natural synergy for the integration of traditional engineering disciplines.

Several universities around the world have developed mechatronics courses and mechatronics research laboratories. Some universities offer mechatronics programs at the undergraduate or graduate level. In the College of Engineering at North Carolina State University, mechatronics courses and research projects have been developed over the past several years. To support both the growing teaching and research interests in the field of mechatronics as well as to support the needs of industry and the State, and demand from the students, a Graduate Program in Mechatronics has been developed. Existing courses are drawn upon in the Department of Electrical & Computer Engineering and the Department of Mechanical & Aerospace Engineering to form a concentration in mechatronics at the graduate level. Further, the program is designed with flexibility to evolve by capitalizing on the strengths of the departments with the changing research and development community, while maintaining the synergy and integration in both coursework and research activities.

BACKGROUND

There are several universities around the world that offer one or more courses in mechatronics at the graduate level. Further research activities in mechatronics continue to flourish throughout the world in both academia and in the industry. An excellent reference that summarizes the mechatronics programs throughout the world is by Acar [1]. Some of the schools with strong research programs in mechatronics offer only a few graduate courses

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(for example, Tech University of Denmark, the University of Helsinki and Loughborough University in the UK) [1]. Several universities offer a Master of Engineering Program in Mechatronics in UK and Europe [1].

Key features of the curricula are:

- The program offers integrated core courses that cover the basic fundamental material related to mechatronics.
- Special Emphasis is placed on projects which facilitate integration and design aspects of mechatronics.
- The program offers elective courses to allow the graduate students to focus on areas of interest.

King's College in London offers the most integrated program of core courses for those International Universities surveyed [2]. Their program involves six compulsory courses listed below:

- *Robotics and mechatronic devices*: modeling and analysis of typical mechatronic devices.
- *Dynamical systems and simulation*: modeling and analysis of lumped parameter dynamical systems.
- *Embedded microprocessors and real-time systems*: embedded microcomputers and real-time software design.
- *Sensors and actuators*: sensors, actuators and interfacing; system integration.
- *Advanced dynamics and control systems*: dynamics and control mechanisms.
- *Design of mechatronic systems*: design and fabrication of a wide variety of mechatronic devices.

The main features of the programs surveyed at the international level are that they are usually offered as an interdisciplinary program and may not be offered under the MAE or ECE programs, emphasize system and production approaches to mechatronics; most of the programs offer a small core of courses to allow for specialization; and some universities also offer courses in the areas of vibration analysis, process control design management and business management to supplement the core mechatronics courses.

For the engineering universities in the United States surveyed, the number of schools offering a graduate level mechatronics program is small. Many universities emphasize the mechatronics research activities but only offer one or two courses in mechatronics. Two universities have formal programs in mechatronics. San Jose State University has a comprehensive undergraduate program in mechatronics and offers six graduate courses related to mechatronics. Georgia Institute of Technology has the most elaborate graduate program in mechatronics of the US universities surveyed. GIT has 33 graduate courses in the area of Automation and Mechatronics. An interesting note is that the program is offered through the Mechanical Engineering Department although the program included electrical engineering and computer science courses. The emphasis in GIT's program is in robotics, and process control. However, none of them offer a graduate degree with mechatronics concentration in the United States.

NCSU PROGRAM

At NC State University, we set out to investigate the possibility of developing a graduate degree program in response to the demand from students and industry. The dean of engineering appointed an interdisciplinary committee consisting of faculty from mechanical and aerospace engineering, electrical and computer engineering, civil and environmental engineering, and industrial engineering. The committee debated on issues ranging from: What would the curriculum look like? Who would administer it? What resources are required? Who would 'own' the program? and most important of all: How can we assure academic depth in coursework that is achieved in a traditional master's degree in disciplines such as mechanical or electrical engineering while providing the breadth needed to be an effective mechatronics engineering program?

First, we had to be clear that we are neither trying to produce a generalist who has taken a disjointed set of courses with half the coursework in mechanical engineering and the other half in electrical and computer engineering, nor are we trying to produce a combined mechanical and electrical engineer who has taken twice as many courses and essentially earns a dual master's degree in mechanical and electrical engineering.

Thus, our program mission is to produce a mechatronics engineer who has taken a balanced set of courses covering the areas of:

- mechanics (kinematics, mechanical design principles, CAD, design for manufacturability, etc.)
- electronics (analog and digital circuit design, design with discrete components including sensors and actuators)
- controls (control circuitry, digital control systems, modeling and simulation)
- computers (microcontrollers and embedded processor systems, interfacing and data acquisition, real-time software tools)
- design integration (ability to integrate the technologies in a synergistic way to produce useful designs, build, and demonstrate the feasibility).

The students already have a single discipline bachelor's degree so that they have a solid foundation in mechanical engineering or electrical engineering. Further, we believe that a student coming into this program will have a bias towards mechanical or electrical sciences while trying to explore and strengthen, as much as possible, their skills in the other discipline. This hypothesis is based on observation that several of the current graduate students in mechanical engineering strengthen

their electronics and computer interfacing skills rather than getting away with minimal number of courses in electrical sciences, although they were seriously handicapped in the beginning to handle graduate electrical engineering courses.

Hence the curriculum had to be carefully crafted with the following goals:

1. The curriculum should provide the opportunity to develop same depth in the discipline of bias for the student as would have been achieved in a traditional degree.
2. The curriculum should recognize and mandate the coursework in constituent areas of mechatronics while providing choices within each constituent area so as to make the curriculum not overly restrictive, but have a distinct character.
3. The curriculum should involve at least one 'hands on' course, preferably, a design experience to appreciate the integrated nature of mechatronics.
4. The thesis work should be of interdisciplinary nature, judged by the formation of the committee in which members must be from more than one discipline and all members should feel that they are able to contribute and direct the research of the student.

We arrived at five constituent areas that are important to the mechatronics curriculum, namely:

- applied mechanics
- control of mechatronics systems
- dynamics of mechanical systems and actuators
- instrumentation and sensors
- microcontrollers and embedded systems.

Our traditional graduate program in mechanical or electrical engineering consists of a total of 30 credit-hours with 15 credit-hours of coursework required in the major area, 6 credit-hours of thesis work, and 9 credit-hours of elective courses work. While a traditional Master's degree does not place any restriction in the courses the students can take as long as they can meet the 24 credit-hour requirement as mentioned above, we propose a core curriculum for mechatronics requiring students to take courses in all the five areas and follow it up with a capstone design course focused on integration and a multidisciplinary Master's thesis. Flexibility is offered by listing multiple courses in each core area. Thus our graduate program can be described as follows.

GRADUATE DEGREE REQUIREMENTS

A concentration in mechatronics within the Master of Science degree program in the Department of Electrical and Computer Engineering and in the Department of Mechanical and Aerospace Engineering at NC State University provides the following guidelines [3].

Topics in mechatronics (core courses): Select at least one course from each of the following areas—total of 15 credits:

- **Applied Mechanics**
- Principle of Structural Vibration
- Noise and Vibration Control
- Finite Element Method I
- Mechanics of Composite Structures
- Advanced Machine Design I
- Fracture Mechanics
- Analytical Methods in Structural Vibration
- **Control of Mechatronics Systems**
- Linear Control and Design for MIMO Systems
- Principles of Mechatronic Control
- System Control Engineering
- Multivariate Linear systems theory
- Advanced Feedback Control
- **Dynamics of Mechanical Systems and Actuators**
- Design of Electromechanical Systems
- Mechanics of Machinery
- Real-time Robotics
- Industrial Robotics
- **Instrumentation and Sensors**
- Analog Electronics
- Analog VLSI
- Digital Electronics
- Computer Vision
- Digital Image Processing
- Instrumentation in Sound and Vibration Engineering
- Metrology for Precision Manufacturing
- **Microcontrollers and Embedded Systems**
- Distributed Real Time Control Systems
- Digital Systems Interfacing
- Advanced Microprocessors Systems Design
- Design of Electronic Packaging and Interconnects.

Electives: Select two courses supplement the student's program in mechatronics—total of 6 credits). This provides flexibility to strength a single area of interest and obtain substantial depth by taking sequential advanced courses or take areas of interest to create further breadth as desired by the student.

Mechatronics design course in MAE or ECE (hands-on practice) (3 credits): This course brings together the essence of mechatronics through emphasis on hands on work designing, analyzing, building, and testing a prototype mechatronic system.

Mechatronics thesis research (total of 6 credits): Interdisciplinary thesis committee to ensure crossover of technical content across at least two constituent areas.

Other guidelines: A course in one area may not be substituted with a course listed in another topical area. However, a special topics course or other

equivalent courses may be substituted for a course in the topical area upon approval of the mechatronics program administrators, after determining that the course content will satisfy the need in the topical area. A student in the mechatronics concentration will also meet the overall departmental degree requirements, namely, fifteen credit hours in the department awarding the degree.

ADMINISTRATION

Being interdisciplinary in nature, there are two possibilities of administering the program:

1. A separate entity outside the departmental boundaries administering the program.
2. A joint committee among departments administering the program while details of admission and enforcement of degree requirements are done departmentally.

If the mechatronics program administration is a separate body outside of the departments, it will require a complete duplication of the administration structure and require additional resources. Hence it was decided not to create a separate structure, but to house the program under the graduate programs in both the Mechanical and Aerospace Engineering and the Electrical and Computer Engineering Departments. In other words, the admission, and enforcement of requirements for graduation will be carried out within the two departments by the graduate program directors, while the students simply declare themselves as taking mechatronics majors by satisfying the requirements and communicating with the program director in each department. Thus, there is very little change in the way the program graduate program is administered at present.

Sustained graduate courses are developed generally through faculty research interests. It was clear that we cannot draw up a course syllabus for the program and look for faculty members to teach it. We had to draw on our existing courses while providing a mechanism for gradual evolution into an ideal mechatronics program. The mechanism at NC State is that of 'special topics'. These are courses offered by faculty members from time to time to capitalize on their current and developing research interests. Some of these courses show sustainability by repeated offering and takers and make it into the permanent course list. While our program cannot be based on special topics courses alone, it is the chosen mechanism for continuous evolution of the mechatronics program. Thus, a student may take a special topics course offered during his or her stay on campus provided the course content is approved as equivalent or meeting the requirements in a core area by the program or graduate director. If the course becomes viable and is promoted to a permanent course in the catalog, the course is added to the core course list. For the same reason, we may remove courses from the core course list if the faculty offering the course retired or the course is no longer offered. This mechanism of renewal and continuous change is necessary to maintain the program to be current and in step with the research trends in the industry and faculty interests.

A feasible course of study plan for a student from mechanical engineering and one from electrical engineering are shown in Tables 1 and 2, respectively.

RESOURCES MANAGEMENT

We found out that our approach requires few additional resources. Currently, the Department of Electrical and Computer Engineering and the Department of Mechanical and Aerospace Engineering have initiated mechatronics laboratories that will serve as the focal point for mechatronics design projects. We are working to establish a coherent collaborative effort from the two departments to share resources (equipment, supplies, and faculty and staff time) in order to minimize duplication of resources.

Table 1. Sample program for the MS degree in MAE (mechatronics concentration)

	Requirement category satisfied
First Year: Fall Semester	
Principles of Structural Vibration	Applied Mechanics
Principles of Mechatronic Control	Control of Mechatronic Systems
Finite Element Analysis I	Elective I
First Year: Spring Semester	
Metrology for Precision Manufacturing	Instrumentation and Sensors
Mechatronics Design	Integration and Hands on Practice
MEMS Design	Elective II (Special Topic)
Second Year: Fall Semester	
Electromechanical System Design	Dynamics of mechanical systems & actuators
Thesis	Thesis
Second Year: Spring Semester	
Digital Systems Interfacing	Microcontrollers and Embedded Systems
Thesis	Thesis

Table 2. Sample program for the MS degree in ECE (mechatronics concentration)

	Requirement category satisfied
First Year: Fall Semester	
Principles of Structural Vibration	Applied Mechanics
Electromechanical Systems Design	Dynamics of mechanical systems & actuators
Advanced Feedback Control	Control of Mechatronic Systems
First Year: Spring Semester	
Image Processing	Elective I
Adv. Microprocessor systems design	Microcontrollers and Embedded Systems
Biomedical Instrumentation	Instrumentation and Sensors (Special Topic)
Second Year: Fall Semester	
Mechatronics Design	Integration and Hands on Practice
Thesis	Thesis
Second Year: Spring Semester	
Embedded Systems Design	Elective II (Special Topic)
Thesis	Thesis

A joint ECE-MAE faculty-working group serves as the focal point for this collaboration. The committee essentially coordinates the mechatronics program. This committee reviews topical areas of mechatronics as the technology and demands change and revise the curriculum appropriately to meet the student's interests and technical community's needs. The committee identifies laboratory needs to support the mechatronics program and work with industry contacts to get input and help for the program.

FUTURE DIRECTIONS

As mentioned earlier, the concentration in mechatronics may evolve into a more synergistic program as faculties from both the departments continue to enhance the integration of teaching and research between them. It is envisioned that courses will be jointly listed in both Mechanical and Aerospace Engineering and Electrical and Computer Engineering Departments. Background and preparatory information for students planning to enter this program will be available in the form of self-paced interactive web-based learning modules. Encouragement of faculty to develop such modules will be very important to accomplish this goal. Distance education is also a potential direction that this program may take for a widespread reach.

SUMMARY AND CONCLUSIONS

We have described the evolution of mechatronics into a graduate degree program in the United States, particularly, at North Carolina State University, jointly administered by the Departments of Mechanical and Aerospace Engineering and the Electrical and Computer Engineering. We found out that the only reasonable way to get started with such a focused program was to identify existing courses related to mechatronics and develop the required core curriculum, unlike the general mechanical or electrical engineering degrees where only the credit-hour requirements are stated. The fact that these courses are from existing graduate courses and that the electives can be used by students to gain additional depth or breadth in his or her curriculum, we have ensured that the program does not compromise the academic depth for the sake of breadth, which was the primary concern of faculty members in the committee. What we have done is to essentially direct the student to take courses in all the constituent areas, while giving the student plenty of choices in each group and keeping the possibility of adding special topics courses on a case-by-case basis as they are offered. Further, it was ensured that the overall degree requirements for a mechanical or electrical engineering graduate degree are met as an overriding policy to assure faculty that this is not a radical change, but an adjustment to reflect the sign of times.

A concentration in mechatronics within the graduate program in mechanical or electrical engineering is the fastest way to address the needs of the industry and students, as we have found. We have built in a mechanism for growth and evolution through a process of constant curriculum revision as new areas related to emerge as a result of faculty research interests and industry needs.

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