A COLLABORATIVE AND INTERDISCIPLINARY APPROACH TO MECHATRONICS

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Abstract

Mechatronics continues to gain currency throughout the world as a unique field of study. As this happens, more and more universities within the United States are expanding their offerings to include this valuable multi-disciplinary field. This paper examines the ongoing effort to develop a mechatronics track within the mechanical engineering and electrical engineering majors at the United States Military Academy (USMA) at West Point, New York. The physical, military, and educational requirements at USMA present unique challenges to expanding course offerings. Adding a mechatronics track requires incorporation of at least one additional course into already demanding existing requirements, as well as some re-arranging of other required courses. In order to leverage talents and resources already in place, this effort is undertaken jointly by the Departments of Civil and Mechanical Engineering (CME) and Electrical Engineering and Computer Science (EECS). Consideration is made of the overall educational philosophies of both the Academy and the departments involved. Accreditation concerns must also be addressed in accordance with the standards of the Accreditation Board for Engineering and Technology (ABET).

Background

"Mechatronics" has been defined many ways[1], but all of these definitions emphasize the interdisciplinary nature of this engineering field. The crossroads of mechanical engineering (ME) and electrical engineering (EE), mechatronics is an integrative field that provides an understanding of mechanical and electrical subsystems united by a control algorithm (see Figure 1). With the rapid and continued advancement in integrated circuit technology, more and more devices have the capability to sense the environment, make decisions based upon coded instructions, and take some physical action within the environment. Machines with this flexible control capability can be classed as mechatronic systems. Therefore, it is important to produce engineers who are versed in all of the contributing disciplines necessary to create such integrated devices.

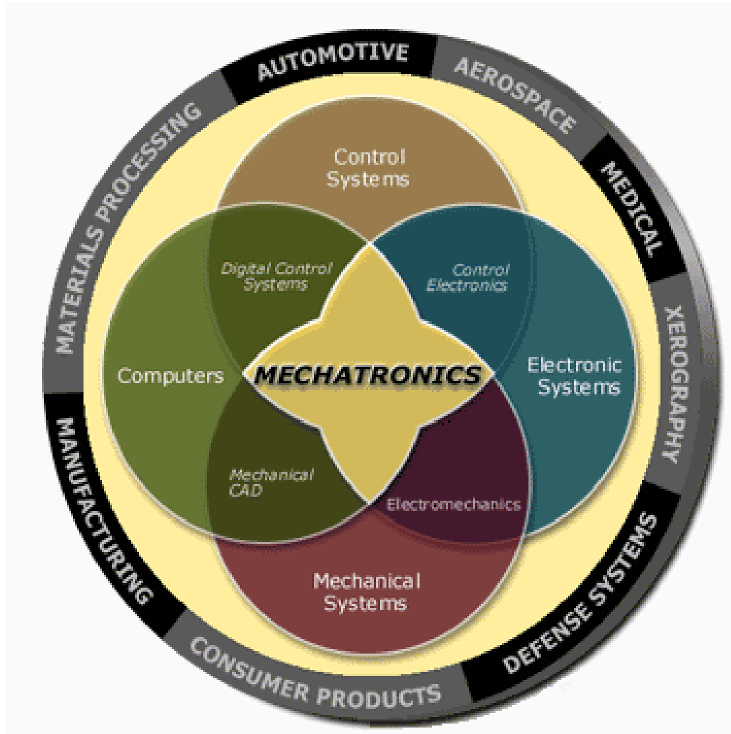

Figure 1. Mechatronics lies at the intersection of several engineering fields[2].

The importance of an electrical or mechanical engineer's ability to integrate the constituent fields within mechatronics is difficult to overstate. In a series of papers on "The Future of Engineering Education," Richard Felder, et. al., discuss several areas of needed change in engineering education. Among them is a call for increased emphasis on multidisciplinary projects and programs: "All authentic problems and all viable solutions today are multidisciplinary and, therefore, engineers must be skilled and educated at working effectively with and in other disciplines..."[3].

There has been wide current public interest in mechatronics, as evidenced by the response to the recent "Great Race" sponsored by the Defense Advanced Research Projects Agency (DARPA). For several weeks, articles appeared almost daily in the New York Times and other national newspapers and periodicals covering the progress of the autonomous vehicles competing in the desert for $1 million prize money[4, 5, 6].

Mechatronics is important to the United States Army for several reasons. First, the Army is currently undergoing one of the most significant transformations in its history, a transformation based largely on advancements in sensor technology, communications, lethality, mobility, and survivability. The ability to gather and process information about an increasingly complex battlefield environment is vital to the success of our soldiers around the world. Mechatronic devices such as robots, unmanned ground vehicles (UGV's) and unmanned aerial vehicles (UAV's) provide a powerful option for gathering that information.

Second, the Army's ongoing effort to modernize can leverage the advantages offered by mechatronic systems. The capability to provide flexible, adaptive controls for mechanical systems can prolong the life of Army hardware.

As a primary source of officers for the Army, the United States Military Academy has the responsibility to produce officers prepared to function in an increasingly technologically advanced Army. During their careers, USMA graduates will be the leaders who employ mechatronic devices. It is vital that they understand the basic concepts behind these technologies.

Beyond the Army's need for technologically competent officers, however, another motivation for the current effort has been the desire to integrate the engineering curriculum. Educating engineers who can function in a multi-disciplinary environment directly supports the program outcomes delineated by the Accreditation Board for Engineering and Technology (ABET) in their Criteria for Accrediting Engineering Programs[7]. The need for multidisciplinary integration at West Point is explicitly stated in the *Operational Concept for the Academic Program of the United States Military Academy*[8]. "As the sole institution of higher education in the nation whose primary responsibility is to educate cadets for career service as professional Army officers, West Point incorporates a dynamic, challenging, and integrated curriculum, organized around a set of interdisciplinary goals drawn directly from Army needs." Further, the USMA Dean of the Academic Board, Brigadier General Daniel Kaufman, states in his Vision for the Academic Program that he envisions an academic curriculum that is "dynamic, interdisciplinary, and integrated"[9]. Within the ME and EE programs, a mechatronics track satisfies all of these requirements.

Perhaps most important of all the reasons for teaching mechatronics, however, was the stated interest among the Corps of Cadets at USMA, as evidenced by a recent survey of first- and second-year cadets. Mechatronics was ranked second among possible new options under consideration.

The combination of all of these motivations (interdisciplinary nature of the field, benefit to the Army, curriculum integration, cadet interest) has led to the current effort to create a mechatronics program at West Point.

Interdepartmental Coordination

The key element to making mechatronics at West Point a reality is the joint nature of the development effort. Personnel from both CME and EECS have worked and continue to work together closely to ensure success. Since mechatronics is fundamentally a multidisciplinary field, this interdepartmental coordination is vital.

There are several precedents for this level of coordination. First, there are several capstone exercises that draw cadets from both departments. The capstone exercise is a final culminating project for first-class cadets (seniors) which allows them to work within an interdisciplinary team to design, build, and test a system. Examples of two such projects, MAGIC (Multi-sensory Autonomous Ground vehicle Intercollegiate Competition) and Battle-bots, are multidisciplinary in nature.

The MAGIC project involves cadets from the ME, EE, Computer Science (CS), and Systems Engineering (SE) majors. For the past several years, cadet teams have produced a vehicle to compete in the Intelligent Ground Vehicle Competition each year at Oakland University in Rochester Hills, Michigan. The Battle-bot project is modeled after the popular television series on the Comedy Central network. This project brings ME and EE cadets together to design and build a remote-controlled battle-bot. At the end of the academic year, these bots compete to determine the king of the ring. In the future, the Battle-bot project will also include CS cadets in an effort to make the vehicles semi-autonomous.

Another interdepartmental precedent is West Point's course in classical automatic controls. This course has been taught jointly by CME and EECS for several years, and serves as a model for development of and teaching the new mechatronics course.

This controls course (numbered XE472 rather than EE or ME472 to denote its interdepartmental nature) normally has an enrolment of 30 to 50 cadets, which with the Academy's design for small section size results in two to three sections of about 15 students per semester. These sections are divided between two instructors – one from EE and one from ME. The departments rotate (normally by semester) which of the two instructors will act as course director. The course director is responsible for the administrative details of the course, to include distribution of the grading, assignment revision, and exam writing workloads.

At the Academy level, a course cannot exist in limbo between two departments. Therefore, even though XE472 is a joint course, it resides for administrative purposes in EECS. While this official ownership might lend itself to dominance of the course by the EECS department, in the authors' experience an ME instructor serving as course director has had little difficulty maintaining the balance between the two departments. This is due in large part to the clearly defined overarching objectives for the course. By jointly establishing the learning objectives of XE472, CME and EECS have determined a common framework for teaching the course.

This interdepartmental cooperation is somewhat unique to USMA. At most universities in the United States, if a mechatronics course exists it is resident in the mechanical engineering department. There are few truly interdepartmental programs.

Curriculum development

The fundamental mission of the United States Military Academy is "to educate, train, and inspire the Corps of Cadets so that each graduate is a commissioned leader of character committed to the values of Duty, Honor, Country; professional growth throughout a career as an officer in the United States Army; and a lifetime of selfless service to the Nation."[8] In order to accomplish this, the Academy requires more of its students than most any other institution of higher learning in the world. Cadets must satisfy the requirements of not only the Academic

Program, but also the Military and Physical Programs. In order to graduate leaders of character for our Army and our Nation, USMA must train the Corps of Cadets in all of these areas.

Both the CME and EECS departments have to remain cognizant of the fact that we are educating Army officers, not just engineers. While completing their military and physical requirements, cadets must simultaneously complete an academic curriculum on par with any in the nation. Within ME and EE, cadets complete a total of 43 courses over four academic years (it is the very rare exception when a cadet is allowed more than four years to graduate). In combination with the military and physical requirements, these stringent academic standards provide balance to the cadet education. Unfortunately, these requirements have traditionally left little room for flexibility within either major.

As of 2003, the curriculum within CME at West Point gave the cadets two possible options within ME: Aeronautical and General (Automotive). The curriculum within EECS allowed four options within EE: Power and Controls, Communications, Information Assurance, and Computer Architecture.

Figure 2 shows the coursework template for the ME major in use through the class of 2006, and Figure 3 shows the template for the EE major. Numbered and italicized courses represent courses required for the major, and unnumbered courses are core courses required of all cadets. As can be seen, the schedule is full almost to the point of having no room to add an additional course.

4th Class (Fall '02)	4th Class (Spring '03)	3rd Class (Fall '03)	3rd Class (Spring '04)	2nd Class (Fall '04)	2nd Class (Spring '05)	1st Class (Fall '05)	1st Class (Spring '06)
Chemistry	Chemistry	Geography	*CE302 - Statics & Dynamics*	*CE364 - Strength of Materials*	*ME362 - Fluid Mechanics*	*EE301 - Intro to EE*	*ME400 - Seminar*
Math	Math	Math	*MA364 - Eng. Math*	*MA206 - Probability & Statistics*	*ME380 - Eng. Materials*	*ME402 - Design*	*ME496 - Capstone*
English	Literature	Physics	Physics	*ME301 - Thermo-dynamics*	*ME401 - Design*	*ME480 - Heat Transfer*	*XE472 - Controls*
Info. Tech.	General Psych	Fitness Leader	Philosophy	*ME370 - CAD*	*ME486 - Vibrations*	*ME492 - Power Trains*	*ME Elective*
History	History	American Politics	Political Science	International Relations	*ME491 - Power Plants*	History	History
	Military Science	Foreign Language	Foreign Language	English	Leadership		Law

Figure 2. ME major course requirements for the Class of 2006 (general (automotive) track shown).

4th Class (Fall '02)	4th Class (Spring '03)	3rd Class (Fall '03)	3rd Class (Spring '04)	2nd Class (Fall '04)	2nd Class (Spring '05)	1st Class (Fall '05)	1st Class (Spring '06)
Chemistry	Chemistry	Philosophy	*EE360 - Digital Computer Logic*	*EE302 - Intro to EE*	*EE362 - Intro to Electronics*	*EE401 - Electronic System Design I*	*EE402 - Electronic System Design II*
Math	Math	Math	*MA364 - Eng. Math*	*EE375 - Computer Architecture*	*EE381 - Signals & Systems*	*EE462 - Electronics Design*	*EE400 - Seminar*
English	Literature	Physics	Physics	*EE383 - EM Fields*	*EE477 - Comm. Systems*	*EE478 - Telecomm.*	*EE486 - Solid State Electronics*
Info. Tech.	General Psych	Fitness Leader	Terrain Analysis	*MA206 - Probability & Statistics*	*CE364 - Strength of Materials*	*EE377 - Electric Power Eng.*	*XE472 - Controls*
History	History	American Politics	Political Science	*CE302 - Statics and Dynamics*	International Relations	History	History
	Military Science	Foreign Language	Foreign Language	English	Leadership		Law

Figure 3. EE major course requirements for the Class of 2006 (communications track shown).

In the fall of 2003, both CME and EECS began work on the possibility of providing more concentration possibilities for students within the ME and EE majors. In ME, a team considered options that included Bioengineering, Mechatronics, Computational Engineering, Engineering Management, Energy Systems, and Nuclear Engineering. Surveys of first- and second-year cadets were conducted in order to determine the level of interest in these various fields. Based on these results, the subdisciplines team focused their efforts on the four most popular and viable fields, appointing departmental subject matter expert for each field.

As a result of this development process, the template for the ME and EE majors has been revised to enable more flexibility within the curriculum. Beginning with the Class of 2007, there will be six tracks available to ME majors (Mechatronics, Aeronautical, Automotive, Bioengineering, Energy Systems, and Engineering Management), and five available to EE majors (Mechatronics, Communications, Information Assurance, Computer Architecture, and Electronics).

Since both departments discovered considerable interest in the field of mechatronics, the two efforts came together very early in the curriculum development and approval process. Representatives from both EECS and CME discussed possibilities for creating the new mechatronics track jointly. First, it was necessary to determine if a completely new course was required. With budgetary and personnel constraints playing a major role, both departments preferred not to create a new course if possible.

When examining the curriculum from each department, we determined that any track in mechatronics would be incomplete if we drew only from existing courses. A capstone course that brought all the elements of mechanical and electrical engineering together would be necessary. This new course was designated XE475, again to denote the interdisciplinary nature of the course.

Figures 4 and 5 show the revised five-semester template for the mechatronics track within ME and EE, respectively. These tracks will be available for the Class of 2007 and beyond. Highlighted courses are those that have changed as a result of the curriculum development process.

4th Class (Fall '02)	4th Class (Spring '03)	3rd Class (Fall '03)	3rd Class (Spring '04)	2nd Class (Fall '04)	2nd Class (Spring '05)	1st Class (Fall '05)	1st Class (Spring '06)
Chemistry	Chemistry	Geography	*CE300 - Statics & Strengths*	*CE364 - Mechanics of Materials*	*ME380 - Eng. Materials*	*EE360 - Digital Computer Logic*	*ME400 - Seminar*
Math	Math	Math	*MA364 - Eng. Math*	*EE301 - Intro to EE*	*ME370 - CAD*	*XE472 - Controls*	*ME496 - Capstone*
English	Literature	Physics	Physics	*ME306 - Dynamics*	*ME403 - Design*	*ME404 - Design*	*XE475 - Mechatronics*
Info. Tech.	General Psych	Fitness Leader	Philosophy	*ME311 - Thermal-Fluid Systems I*	*ME312 - Thermal-Fluid Systems II*	*ME480 - Heat Transfer*	*ME Elective*
History	History	American Politics	Political Science	*MA206 - Probability & Statistics*	International Relations	History	History
	Military Science	Foreign Language	Foreign Language	English	Leadership		Law

Figure 4. ME major course requirements for the mechatronics track (changes from Class of 2006 template highlighted).

4th Class (Fall '02)	4th Class (Spring '03)	3rd Class (Fall '03)	3rd Class (Spring '04)	2nd Class (Fall '04)	2nd Class (Spring '05)	1st Class (Fall '05)	1st Class (Spring '06)
Chemistry	Chemistry	Philosophy	*EE360 - Digital Computer Logic*	*EE302 - Intro to EE*	*EE362 - Intro to Electronics*	*EE401 - Electronic System Design I*	*EE402 - Electronic System Design II*
Math	Math	Math	*MA364 - Eng. Math*	*EE375 - Computer Architecture*	*EE383 - EM Fields*	*EE462 - Electronics Design*	*EE400 - Seminar*
English	Literature	Physics	Physics	*EE381 - Signals & Systems*	*EE377 - Electric Power Eng.*	*EE486 - Solid State Electronics*	*XE475 - Mechatronics*
General Psych	Info. Tech.	American Politics	Political Science	*MA206 - Probability & Statistics*	*ME311 - Thermal-Fluid Eng.*	*XE472 - Controls*	*EE Elective*
History	History	Foreign Language	Foreign Language	*CE302 - Statics & Dynamics*	International Relations	History	History
			Terrain Analysis	English	Leadership		Law

Figure 5. EE major course requirements for the mechatronics track (changes from Class of 2006 template highlighted).

Within the larger ME or EE curriculum, a cadet chooses from one of the available tracks. Doing so designates three depth elective courses. Within ME, the three depth courses for the mechatronics track are EE360, XE472, and XE475. Within EE, the three depth courses for mechatronics are EE377, XE472, and XE475. EE360 was designated as a depth course for ME cadets because it is important to ensure that students coming from both EE and ME majors needed to have a basic knowledge of the functioning of microcontrollers and computers (all EE majors are required to take EE360). XE472 was designated as a depth course for both majors so that all cadets entering XE475 would have an understanding of modeling systems and designing automatic controls for those systems.

Course development

XE475 is being developed and will be taught jointly by CME and EECS, leveraging the existing talents and resources within both. The first task was to devise a course proposal for approval at the Academy level. This course proposal had to include the course learning outcomes, a learning model, an assessment plan, a course description, and a tentative syllabus. The authors were greatly assisted in this effort by input from Dr. Kevin Craig of Rensselaer Polytechnic Institute in Troy, NY.

In devising the learning outcomes for the new course, it was extremely important to emphasize a balance between theory/analysis and hardware implementation. Physical and tangible understanding of the principles under discussion is vitally important, without neglecting the underlying mathematical formulation of problems. A case-study, problem-solving approach,

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with hardware demonstrations and hardware laboratory exercises, was the method sought for the course.

The learning outcomes were defined as those capabilities the cadets should have upon completion of XE475. These were

1. Apply physical and mathematical modeling (both from first principles and using system identification experimental techniques) to mechatronic system design to analyze mechanical, electrical, electromechanical, fluid, thermal, and multidisciplinary systems.
2. Model various nonlinear and parasitic effects in real dynamic systems, to include backlash, time delay, saturation, Coulomb friction, and unmodeled resonances.
3. Describe the key elements of a measurement system and apply the basic performance specifications and models of a variety of analog and digital mechatronic sensors.
4. Describe the characteristics and models of various electromechanical actuators (brushed DC motor, brushless DC motor, and stepper motor), as well as hydraulic and pneumatic actuators.
5. Describe the programming and interfacing issues in using a microcontroller as a mechatronic system component.

These five outcomes were determined in joint consultation between CME and EECS. They dictate the focus of the course and support the overall goals stated above of emphasizing physical understanding grounded in mathematical theory.

Having defined the learning outcomes, the next step of course development was to develop a learning model for how these outcomes would be accomplished. XE475 is structured to incorporate previous theoretical courses and enable “dirty hands” understanding of real-world components. The process necessary includes an introduction to nonlinearities and real systems and the laboratory work needed to understand them. Finally, the content of the course was further developed into a tentative syllabus (see below).

An assessment plan was necessary to formalize the dynamic and ongoing course development once XE475 was being taught. While students need feedback in the form of homework, exams, and other graded requirements to enable their learning, instructors need feedback to constantly improve the course. This feedback comes from both cadet performance on assigned work as well as end of term feedback surveys. These surveys are automated through the Academy’s web-based system.

The course description for XE475 provides a brief overview of the course objectives as well as a list of the pre-requisites necessary before a cadet may enroll in the course. Determining these pre-requisites was a challenge, as mechatronics draws from so many fields within engineering.

What should a student know before taking an undergraduate mechatronics course? They should certainly have a core math and science background appropriate to any engineering student. They will need a basic understanding of modeling dynamic systems, as well as an introductory course in electronics. Students need to have familiarity with automatic controls, and since mechatronics is heavily dependent upon computer controls an understanding of microcontroller function and basic programming is vitally important. Having determined these requirements, it was agreed that the appropriate pre-requisites for XE 475 would be EE360 (Digital Computer Logic) and XE472 (Dynamic Modeling and Controls). EE301 / EE302 (Introduction to Electrical Engineering) would have been included as a pre-requisite, but it is required for enrollment in XE472 and inclusion would have thus been redundant.

When writing the tentative syllabus for XE475, we broke the course down so that we could meet all of the learning goals. We decided to include the following blocks of instruction:

1. Modeling / Parasitic Effects
2. Power generation
3. Actuators
4. Sensors
5. Microcontrollers

Each of these five areas has an associated laboratory exercise. The course has a total of 40 lessons (including labs), with two written partial reviews (mid-term examinations) and a term end examination (final exam). CME has taken the lead on developing blocks 1, 3, and 4, while EECS is developing blocks 2 and 5. The entire process will be coordinated to ensure the course is properly integrated. Failure to do so will result in a set of discrete, disconnected blocks that will detract from the students' learning experience.

Future Goals

The curriculum development process which resulted in the adoption of the mechatronics track with in the ME and EE majors at West Point will apply first to the class of 2007. Since XE475 is the final course within the mechatronics track, it will not be taught for the first time until the spring semester in 2007.

As a result of expressed interest among the class of 2006, however, an attempt is being made to offer the course in the spring of 2006. This offering will be done under the title of ME490 (Special Topics in Mechanical Engineering), and will need to account for the fact that few of the cadets taking the course will have completed all of the regular pre-requisites for XE475. More time will need to be spent on digital architecture and automatic control systems. This will most likely come at the cost of depth in the microcontroller block.

Laboratory development is another ongoing challenge. The intent of the laboratory exercises is to expand upon theoretical classwork in a hands-on format. Each of the five blocks will develop the theory behind the major block concept, then deal with real-world application in the associated lab.

These five labs are not independent activities. The practical application provided in the labs will all be associated with one mechatronic system, most likely a robotic platform. This enables a deeper understanding of the integration of these course blocks and their applicability to the overall functioning of the system.

Conclusion

Mechatronics is a field of great importance to the advancement of mechanical and electrical engineering, and provides a fertile field for military technological advancement. USMA's mission to produce leaders for tomorrow's Army necessarily includes a mandate to ensure these leaders understand the basics of the technology they will employ to fight and win our nation's wars. This impetus, along with significant cadet interest, has led to the development of a mechatronics track within the ME and EE majors at West Point.

This course development has been at all stages a joint effort between the Departments of Civil & Mechanical Engineering and Electrical Engineering and Computer Science. This interdepartmental coordination, supported by past successes teaching a joint course, has enabled the leverage of talent and experience from both departments to create a truly interdisciplinary course experience.

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