Development of a Curriculum for Mechanical Engineering Based upon Intelligent Systems and Automation

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Abstract

Realizing the need for mechanical engineering programs to adapt to an ever-diversifying competitive world, the University of Notre Dame is developing a new curriculum that includes focused educational experiences. This focus is based upon the opportunities provided by the synergism between traditional discipline elements and embedded computing in all forms of mechanical systems. These experiences will better prepare students for the continued proliferation of sensing, actuation and control technologies resulting in what are often referred to as intelligent mechanical systems. The primary elements of this curriculum development activity are supporting faculty development and interest, developing infrastructure and facilities, and collaborating with industry in order to integrate elements of intelligent, embedded computing systems across the curriculum. This involves striking a balance between fundamental concepts, algorithm development, hardware, and applications; and this is accomplished by threading these concepts throughout the curriculum. A new facility, the Intelligent Systems and Automation Learning Laboratory (ISALL) has been developed and it supports faculty and students in the development and execution of these new learning experiences.

I. Introduction

"In just five to 10 years' time, the Web will be the preeminent forum for students to receive their class lectures. Thus universities will have to specialize to such a degree that there may be only a handful of them offering lectures, via the Web, in any given area of engineering."[1] So stated Woodie Flowers (MIT professor and ASME's 1999 Edwin F. Church Award winner for eminent service in mechanical engineering education) in his keynote address, "Why Change? Been Doin' It This Way for 4,000 Years!" to a group of mechanical engineering department chairs at ASME's 2000 Mechanical Engineering Education Conference. Flowers went on to say that this specialization will force university faculties to shoulder more of the responsibility for creating highly interactive educational environments, which put more emphasis on activities that can't easily be duplicated on the Web. "Laboratory experience and multi-disciplinary group design projects involving teams of students at the same university and students at other universities may be the kinds of activities that learning institutions will use to distinguish themselves from each other."[1]

While this prediction may be extreme, the call for significant, purposeful, and timely educational innovation is widespread. The University of Notre Dame's Teaching, Learning, and Technology Roundtable, for example, referring in large part to competitive pressures which attend new electronic modes of communication, began its spring 2000 report with the words: "Change in higher education in the future will be rapid and far-reaching, ..."[2] The Accreditation Board for Engineering and Technology, ABET, in response to emerging demands of the new economy, and in anticipation of the need for widespread change, has reoriented its perspective. Most salient in the new *ABET 2000* guidelines are the invitation for the departments to:

- create a distinguishing theme,
- define many of its own educational objectives pertinent to such a theme,
- set its own strategy for assessing success in meeting those objectives,
- use the assessment information to make appropriate changes and,
- document progress in achieving the educational objectives.

The present paper discusses the adoption of such a distinguishing theme in the Mechanical Engineering curriculum at Notre Dame. The revisions are timely but also consistent with the traditional objectives of Mechanical Engineering undergraduate education, as well as consistent with existing strengths and interests of the faculty. The theme, namely the use of embedded microprocessors or other electronic devices to enhance behavior, versatility, and/or efficiency in many of the kinds of systems historically associated with mechanical engineering, represents a quiet revolution that increasingly pervades a range of industries, manufacturing processes, and product designs.

The revised curriculum (shown in summary in Figure 10 at the end of this paper with the directly affected courses highlighted) continues to reflect fully an earlier revolution in technology: the application of calculus to the modeling and understanding the important physical principles. It is the academy that has primary responsibility for ensuring that related insights and analytical tools become part of the mindset of future practitioners, researchers and engineering managers. Because the felt competitive pressures of industry may encourage sheer empirical, phenomenological, or trial-and-error practice for many engineers, provision of a firm, enabling, insight-producing foundation in engineering science must remain as “job 1” in engineering education. More than simply coexisting benignly with this theme, the new emphasis is implemented so as to complement this traditional objective.

Part of the implementation entails the ongoing challenge of connecting analysis with the creative process of design. The microprocessor itself, allowing as it does the application of mathematically based algorithms to meet specific design requirements, helps promote such ability. The curriculum entails many small microprocessor–based design objectives to be assigned in several courses; and it also entails a dedicated course with the specific objective of providing exposure to microprocessor-based strategies in design.

These new elements inevitably reduce marginally the time expressly devoted to engineering-science topics including mathematics; however, the effects of the tradeoff can be minimized by taking advantage of the above prospects of the microprocessor to complement engineering-science education. Furthermore, reformulation of engineering-science-course content, and judicious topic regrouping, makes the reduced classroom time more efficient and effective by emphasizing the broadly unifying aspects of the application of calculus and differential equations to key mechanical-engineering physical principles and control strategies.

Practical considerations associated with implementation of these reforms include cost, faculty involvement, infrastructure and technical support, a transition period, and pertinent input from the kinds of industrial constituents likely to hire our graduates. A grant from the National Science Foundation “Action Agenda for Engineering Curriculum Innovation” program is being used to help underwrite the initial program costs during a three-year transition period. The NSF grant includes funding for faculty training as well as for hiring support staff to assist faculty. The transition period promises to be gradual in that the three years of the NSF grant, which began December 2000, follow a period of four years during which the microprocessor has already been an integral part of all mechanical-engineering Senior Design projects. The three-year period also follows by one year a coincidental move by the College to introduce microprocessor programming into a 2-course First-Year sequence for all Engineering intents.

Another key element is this program is the integration of industry and industry based problems in to the curriculum. This is being accomplished by attempting to team faculty and faculty groups with industry collaborators. One of the first efforts in this area - with Delphi Corporation - ties together issues related to the mechanical and thermal behavior of the embedded processors that permeate advanced automotive systems. These collaborations are in the initial stages but by supporting faculty engagement with such projects, the goal is to make them a central element of the initiative.

Whether or not, as Prof. Flowers predicts, "in just five to 10 years' time, the Web will be the preeminent forum for students to receive their class lectures," the curriculum reforms outlined in this paper are a prudent and timely step.

II. Mechanical Engineering Program Revision

As part of its ongoing curriculum-assessment efforts, a decision was made by the Department of Aerospace and Mechanical Engineering to integrate into the four years of its mechanical-engineering curriculum instruction and direct experience with the application of digital intelligence to mechanical systems. The key hardware element of such capability is an embeddable microprocessor which is a small computer that can be connected to various sensors and actuators, depending upon the system objectives. The intent is to complement the Department's strength -- coursework in the core engineering sciences -- with significant learning regarding imparting digital intelligence to the full range of systems and products considered by mechanical engineering. The new curriculum extends systematic design instruction and team-based design experience across the span of the four-year curriculum.

Most engineering science and mathematics content remains intact; and embeddable microprocessor content is largely the result of several faculty initiatives that have been developing over the last several years. However two all-new design courses have been added to the curriculum. Students will emerge with experience, in data acquisition and design, with the interfacing of embeddable processors with transducers and actuators that represent a range of areas in mechanical engineering: heat transfer, fluid mechanics, solid mechanics, mechanisms, and thermodynamics.

First year

In Fall 2000, two new First Year courses were put into place: EG 111 and EG 112. Taken in the fall and spring respectively, these two courses give "engineering intents" direct, hands-on insight into the various engineering majors offered at Notre Dame, including Mechanical Engineering. Before learning the mathematical details, students experience the power of simulation and modeling of systems in the form of differential equations as they predict from first principles the trajectory of a projectile released from a launcher, Figure 1. Using their own numerical predictions they make decisions necessary to achieve the required system performance. The two courses are presented in the context of four design projects. Three of the projects use microprocessors for sensing, actuation and control. The ability to exploit this technology to make their designs “smarter” is demonstrated, for example, with the design of a simple vehicle with an embedded processor, thus enabling simple kinds of sensing and real-time decision making during vehicle motion. The potential of the combination of analytical insight into physical component behavior together with the ability to encode suitably connected, onboard processors based upon such insight, is introduced at the very beginning of their studies.

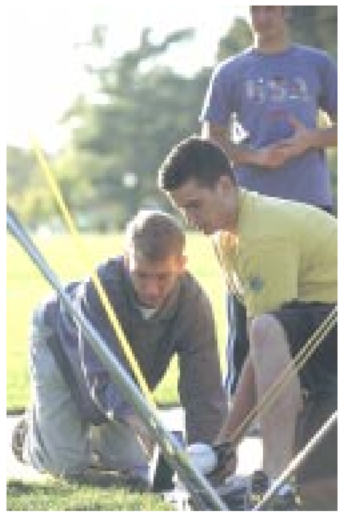

Figure 1. Students ready projectile for launch.

Much of the experimental portion of EG 111 and 112 occurs in the College’s new Engineering Learning Center, Figure 2. This versatile space also supports undergraduate projects in advanced engineering courses. The Learning Center is adding two extensive tutorial modules, developed jointly within the College by an Electrical Engineering faculty member and a Mechanical Engineering faculty member, whereby students and interested faculty will be able to self-learn use of the Motorola 68HC11 processor, with both analog and digital inputs. This will make it easy for students who need introductory, in-depth or supplemental exposure to gain first-hand interfacing and programming experience while working with the learning module.


Figure 2. College of Engineering Learning Center.

Sophomore year

The sophomore year continues to feature initial exposure to courses in the engineering sciences, specifically Engineering Statics, Engineering Dynamics, and Mechanics of Solids. In the first semester, AME 230, Introduction to Mechanical Engineering, exposes students to the application and integration of the varied mechanical engineering disciplines to practical case studies. In this way it represents a focusing of the broader first year experience, which is directed toward the whole of engineering. This new course is designed to: 1) introduce the discipline of Mechanical Engineering, its fundamentals, its subdisciplines and their interaction, and its culture to students; 2) develop modeling skills and a familiarity with design approaches and analytical tools.

Second semester brings AME 250, Techniques of Measurement and Data Analysis, where remote, miniaturized data acquisition begins in earnest. The history of using microprocessors in this course dates back to 1999, when, as part of the course, the sophomore engineers attempted to predict the altitude of a rocket based on data they collected concerning the rocket's drag coefficient and rocket-motor profile, as shown in Figures 3-5. Students applied Newton's second law numerically, comparing its prediction against maximum height as gauged by means of a sextant. But to the degree that the prediction was "off" what was most to blame: The motor model? Atmospheric variations? The numerical integrator? The direct elevation measurement of the sextant to which their prediction was compared? Maybe Newton's law itself is off! Coming to terms with such distinctions is vital for the engineer, particularly the engineer aspiring to achieve useful microprocessor-based control of such a system. And this kind of assessment represents a big part of the point of this course.

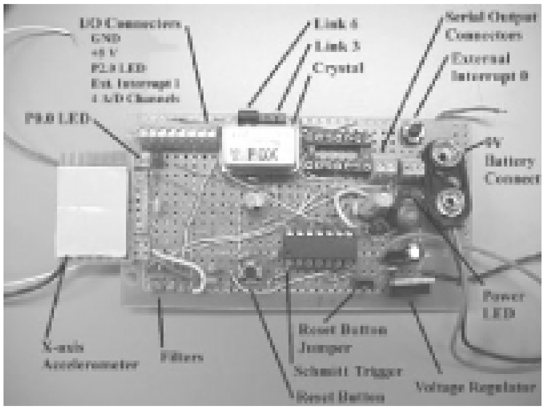

Figure 3. Instrumentation for automated data acquisiton.

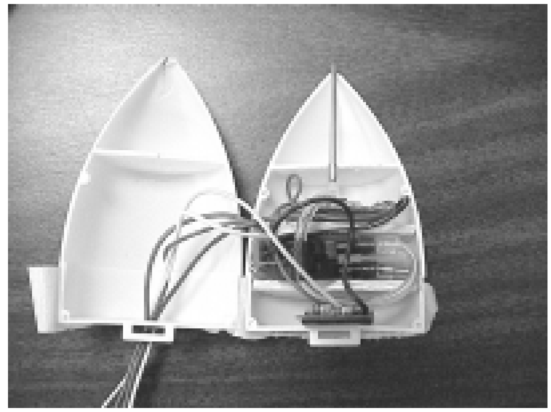

Figure 4. Rocket nose-cone with instrumentation.

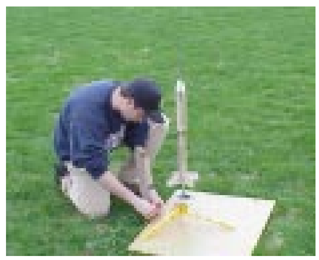

Figure 5. Student readies rocket for launch.

New instrumentation would provide insight into many of these questions as the "rocket science" aspect of the course continued to evolve. The sophomores added two kinds of instrumentation to their rocket: accelerometers and a pressure sensor for measuring air speed. The resulting redundancy of information would allow for increased insight as the engineers pondered the meaning of their results. The use of instrumented rockets is now a permanent part of AME 250. To complement this activity, in the past year this project has been partnered with an ongoing program, "Bits-to-Chips[3]," in which Electrical and Computer Engineering and Computer Science students design, build and fabricate a VLSI chip. This is a two-year, multi-course effort and the ongoing effort is to build a chip capable of analog to digital conversion, on-line determination of altitude via direct numerical integration and data logging and output. Multidisciplinary collaboration is considered a vital element of this new program.

Junior Year

The power of mathematics, and differential equations in particular, to provide understanding and effective modeling of real systems is important for the engineer to appreciate fully. Therefore two, new special junior-level courses have been created for this express purpose. AME 301 and 302 build upon earlier calculus courses in order to develop the methods for solving differential equations in the same context where these equations are motivated physically. The beauty of many of the engineering sciences is that the same mathematics can be applied to widely diverse physical behaviors. Nevertheless, students seem to take most quickly to this new language of mathematics if it is introduced with and motivated by familiar, or at least easily envisioned, physical systems. Therefore this new pair of courses, in addition to including material typically covered in a second differential equations course, will focus on two applications of differential equations that are at once easily envisioned and important to mechanical engineers: mechanical vibrations; and feedback control dynamics.

Computer-Aided Design and Computer-Aided Manufacturing represent another area where mechanical engineering has been altered in the computer age. Another junior-level course, AME 341, provides students with in-depth experience -- experience that is reinforced in subsequent design courses -- in the creative use of drawing and 3D-rendering software tools that comprise “Computer Aided Design”. Adjacent to a 25-computer suite of CAD workstations, the “Computer Aided Manufacturing” side of the course is represented. Here prototype geometries can be fabricated directly from CAD drawings. Included in this lab are material-removing CNC machines, material-building fused-deposition and stereo-lithography machines and coordinate measuring equipment for verification studies. Manufacturing, an emerging strength of the Department, generally is growing in importance in the present era of global competition.

CAD/CAM is just one of many aspects of engineering design that are broached in the Junior Year. AME 345, a new course, builds upon the concepts introduced in AME 230 and CAD/CAM. It provides students techniques for using content from their mathematics and engineering-science courses with the objectives of modeling, analysis, and simulation; and it introduces the role of optimization in the engineering design process. The course is intended to provide a sound theoretical and analytical foundation to design engineering from a systems perspective. The theoretical techniques are balanced with project-based applications and practical engineering skill development such as material selection, data presentation and extracting information from data-bases, catalogs and other sources.

Working in conjunction with the Electrical Engineering Department a significant revision has been made to the formal Electrical Engineering requirement in the program. This new course will contain many of the current elements but will be build around circuit applications involving microprocessors. The course will involve extensive hands-on experience with embedded controllers at the component level and additional programming experiences using this technology.

Senior Year

Though not directly related to the curriculum theme that is the subject of this paper, a parallel development is worth noting. Some students who wish to complement their Mechanical Engineering degree with course content in Business may opt to take one or two of their five Technical Electives with two business-related courses newly offered by the College of Engineering. The first of these provides a foundation in financial, human-resources, supply-chain, organizational and innovation aspects of the modern corporation that are pertinent to the career of a new engineering employee. The second course goes into more depth on these matters, and also touches on issues pertaining to entrepreneurship and business plans. Developing an understanding of how engineering activities fit into the broader social and business context is a complement to this curriculum initiative.

During senior year each student takes a recently expanded AME 470, “Senior Design” course. This 4-credit course earns the moniker “capstone” in several ways. In a creative context, it requires that students call on knowledge acquired in prior design courses, including extensive use of Computer-Aided-Design software. It draws upon previous experience with the ways in which microprocessors may be interfaced with devices and programmed to achieve a particular engineering end. It also requires students to make the sometimes difficult connection between the creative activity of design and the analytical content of engineering science courses: a typical design will call upon the need to perform calculations that draw from two or more engineering-science subdisciplines. Lastly, but surely not least, the experience requires students to put to use in a challenging way a range of communications and human-interaction skills accumulated over the years.

Near the start of the term each senior-design class is divided into groups generally of five to seven. Each group is presented with a “Request for Proposals”; and each is expected to respond with a unique creative design and an ability and intent to produce a prototype. Each design will require an embedded microprocessor as some form of intelligence is required in the problem as stated. Some semesters all groups respond to essentially the same design challenge; other times the groups are asked to respond to a particular one of two or more different aspects of an eventual integrated whole, necessitating inter-group cooperation. The subjects for the project vary by semester, some developed internally and others in collaboration with external industry partners.

The groups’ design proposals take two forms: an extensive written form, with drawings, calculations and discussion; and a design-presentation form. The latter is a formal affair. Practicing engineers in pertinent fields are brought in for a one-day session during which they are asked to critique each group’s proposal, Figure 6. On the basis of this session, and faculty response to the written proposal, groups modify their designs, and prepare to fabricate a prototype for demonstration to class peers and faculty.

Figure 6. Students present designs to industry review panel.

Unlike the earlier CAD/CAM course, where students are exposed to state-of-the-art rapid-prototyping equipment, part fabrication for senior-design prototypes entail an extensive range of more commonly available equipment, Figures 7 and 8. Since prior student experience with the range of such equipment varies considerably, technicians from the College are on hand to instruct students as they gain hands-on experience with machine tools.

The importance of all aspects of planning is emphasized in various ways. Due in part to the limited time available during a semester, the possibility of applying trial and error to "iterate" based on experience with the design is minimal. When the critical time for prototype assembly comes, therefore, astute previous planning becomes a key to success. But the motivation is substantial, as the coming demonstration event will be quite public and conclusive.

Figure 7. Students prepare components for prototypes.

Figure 8. Students assemble prototypes.

The eventual time for testing all prototypes typically occurs in the few days between the end of classes and the beginning of final exams. Results vary widely but learning is intense and lessons learned are memorable. One recent demonstration is shown in Figure 9. Here groups collaborated, with different portions of a manufacturing system intended to introduce via robotic transport a gluing device designed to lay a carefully shaped bead of glue onto an awaiting part. One group created the arm for the robotic docking. Several different groups built "smart systems" for introducing the door to the docking station, on the one hand, and for the mobile, reprogrammable glue-depositing assembly, on the other.

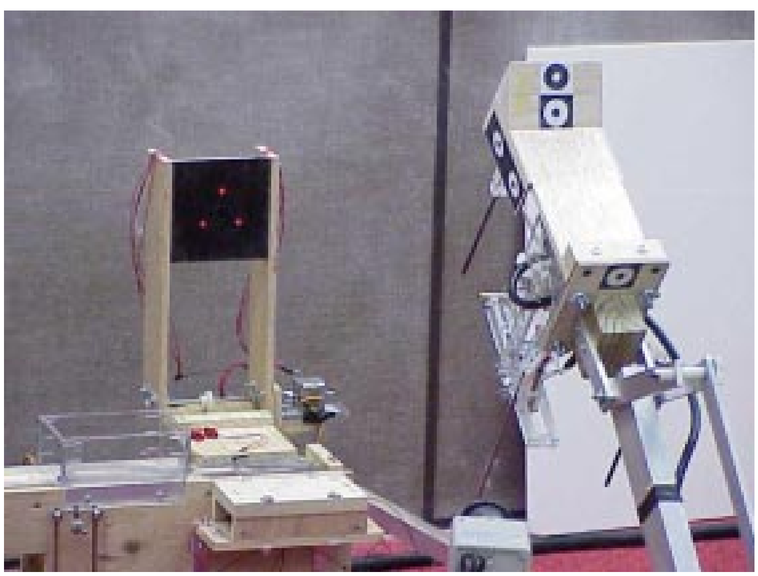

Figure 9. Demonstration of automated glue-laying system.

Some combinations of the groups' systems worked virtually as planned; others did not. But the versatile systems would have been impossible without the enabling virtues of small, embedded microprocessors.

III. Facility Development and Infrastructure Support

In order to implement the changes described herein it was recognized that a significant investment was required to support and facilitate the curriculum goals. In order to enable the faculty who would eventually be responsible for implementing the objectives of the program, both support and infrastructure were required. Though a number of the faculty in the Department supported the initiatives, relatively few had direct experience with this class of computers. Similarly, if the students were to engage in a series of hands-on activities using embedded microcontrollers, space and support for their projects and experiments would be required. Two key elements of the overall program are supported by the NSF grant mentioned earlier: the addition of a microprocessor technical specialist and the development of a dedicated Learning Laboratory space.

A technical specialist has been added to the Departmental staff with the responsibility of supporting the development of the various initiatives described herein. This individual works with faculty and students to support the design and implementation of activities involving the embedded controllers. By working directly with the faculty to develop the applications for particular courses this individual augments the faculty member's discipline-specific expertise and he has been instrumental in introducing many new ideas and capabilities into the educational projects.

The second key addition is the development of the Intelligent Systems and Automation Learning Laboratory, ISALL. This new facility (shown in Figure 11 at the end of this paper) provides a place for students and faculty to develop projects and to work with the technologies that support this curriculum. There are spaces dedicated to project development by the technical specialist, sensor and actuator integration, processor programming, instruction, demonstrations and storage. The facility is designed to operate in conjunction with the College Learning Center mentioned above. Selected activities developed for the undergraduate program will be accomplished in dedicated teaching laboratories such as those described for the sophomore measurements course. Some activities will take place in ISALL and those will occur with the direct support of the technical specialist. Some activities will be developed in ISALL and then implemented in the College Learning Center. These latter activities can then be accomplished by the students outside of regularly scheduled class time in a collaborative, open, learning environment.

IV. Program Assessment

The Class of 2005 will be the first group to complete this new curriculum. They are currently participating in the first year of the program. A variety of initial assessment efforts are part of that program including developing profiles of student attitudes that will allow for a longitudinal evaluation of the influence of the four year program. This section outlines the specific educational objectives associated with the proposed program, the mechanisms by which progress toward these goals will be assessed and the means by which the curriculum will be modified in light of any assessed shortcomings.

For any major curriculum development, the list of specific educational objectives is necessarily long and including herein a comprehensive list is impractical. Although this curriculum-change initiative is directed toward the entire four-year curriculum and since the major modifications will occur during the sophomore and junior years, a short list of two educational objectives is provided for illustrative purposes.

The purpose of the first year is to provide basic exposure to a microprocessor, an introduction to its associated programming and basic use and the concept of intelligent systems and control. The purpose of the sophomore experience is to extend the use of the microprocessor to applications that involve topics from the basic engineering courses and continued development in programming and interfacing. Therefore, by the end of the sophomore year, students will be able to:

- Program the microprocessor as a data acquisition and filtering tool
- Describe the fundamental limitations of the microprocessor (such as processing speed and I/O bandwidth limitations) and particular sensors (sensor dynamics and bandwidth) and identify systems in which the use of a particular microprocessor/sensor combination would lead to inaccurate data acquisition.

In contrast to the sophomore year, by the junior year, students will have taken the two-course sequence in Differential Equations, Modeling and Control, so then they would be able to integrate the topics of rigorous modeling and analysis into the development of control schemes. Therefore by the end of the junior year in the proposed curriculum, students will be able to:

- Apply concepts from feedback control theory such as Routh's stability criterion, root locus plots, Bode plots and lead-lag compensation methods to program the microcomputer to control a mechanical, fluid or thermal system in a specified manner.
- Implement a theoretically effective control law and verify system performance with respect to criteria such as stability, rise time, overshoot, *etc.*, when given a physical system, microprocessor, sensors and actuators.

Broader goals of the curriculum include:

- To further develop expertise within the Department faculty regarding the use of embedded microcomputing systems.
- To enable faculty to incorporate the concepts and use of intelligent systems and the microcomputer into lab, project and classroom activities.
- To enhance formal and informal associations with industrial partners who utilize embedded microprocessor technology in industry.
- To have a significant industrial impact, primarily by producing graduates entering industry with a highly marketable and valuable expertise in embedded microcomputer design for a wide range of mechanical engineering systems.

The process has to implement a mixed-method assessment technique has begun, including both formative evaluations that will be used to modify the structure and implementation of the new program during its early development, and summative evaluations for evaluating the overall outcomes. The goal is to utilize both quantitative and qualitative assessment techniques.[4] As outlined in the Reference 4, proper analysis of the qualitative data, coupled with the "hard" quantitative data, has the benefit of "triangulation" wherein each type of data can serve as a test of the validity of the other. The educational objectives outlined above were formulated in accordance with Bloom's taxonomy of educational objectives.[5] As such, assessment of whether or not students meet the objectives is a straightforward quantitative evaluation, based upon traditional academic measures such as test scores, project demonstrations and reports, *etc*, which result in individual grades and overall class averages. The broader goals are assessed via qualitative techniques, such as scheduled observations, interviews and focus groups. The following table presents the formative assessment schedule that has been developed.

Activity	Schedule	# of Cases
1. Interview project instructors.	Once per month during first year and once per semester subsequently.	12
2. Interview with technical specialist.	Once per month during first year and once per semester subsequently.	12
3. Student examinations, project demonstrations and reports.	Three times per semester, on average, for each class (first year students through seniors).	72
4. Student course evaluations.	Twice per semester for each class.	48
5. Student focus groups.	Twice per semester for each class during the first year and once per semester subsequently.	32
6. Interview with industry partners.	Once per semester.	6
7. Instructor focus group.	Prior to the start of each semester.	6
8. PI, co-PI assessment meeting.	At the end of each semester.	6

Table 1: Project Formative Assessment Plan.

The summative assessment will be comprised of a final interview with department instructors, a final interview with the technical specialist and industry partners and a final instructor focus group meeting. Furthermore, quantitative data relating to student performance (grades) and course evaluations will be summarized and tabulated.

This information will be used determine appropriate modifications of the program, particularly in light of deficiencies determined by the assessment. Any response is clearly highly dependent upon the nature of the deficiency. Since, one of the key elements of the revised curriculum consists of microprocessor-based projects, the deficiencies indicated by interviews, focus groups or objective student performance would be primarily addressed by modifying the content, nature and/or quantity of the microprocessor-based projects and modifying pedagogical techniques.

V. Summary Comments

The new curriculum outlined in this paper seeks to create a general competence and confidence on the part of Mechanical Engineering graduates - beginning with the Class of 2005 - in the application and creative use of intelligent systems and automation implemented in the form of embedded microproprocessors. The goal is to provide the students with the capability to enhance the behavior of the wide class of systems influenced by mechanical engineers. This is being accomplished by threading throughout the curriculum specialized experiences that allow the students to integrate the traditional mechanical engineering disciplines with those manifested in new and emerging systems. Central to this effort has been the developed of support mechanisms and infrastructure to assist faculty and students as well as the implementation of assessment techniques to evaluate the influence of these changes.

VI. Acknowledgments

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Semester					
1	Calculus I	Humanities/Social Science	Chemistry I	**EG111 Intro to EG Sys I**	Composition
2	Calculus II	Physics I	Chemistry II	**EG112 Intro to EG Sys II**	University Seminar
3	Calculus III	Physics II	AME225 Mechanics I	**AME 230 Intro to Mech Eng**	Humanities/Social Science
4	Linear Algebra/ Diff EQ	**AME250 Measurements & Data Analysis**	AME226 Mechanics II	**AME236 Solid Mechanics**	Humanities/Social Science
5	**AME 301: Diff EQ, Modeling and Control I**	AME327 Thermodynamics	AME 341 CAD/CAM	**AME340 Mechanical Design**	Humanities/Social Science
6	**AME302: Diff EQ, Modeling and Control II**	AME334 Fluid Mechanics	**EE224 Elec. Engineering**	**AME345 Design and Manufac.**	ME Specialization
7	Materials	ME Specialization	AME339 Kinematics and Dynamics	**ME Specialization**	Humanities/Social Science
8	AME439 Heat Transfer	ME Specialization	ME Specialization	**AME470: Senior Design Project**	Humanities/Social Science

Figure 10. Revised Mechanical Engineering Curriculum.

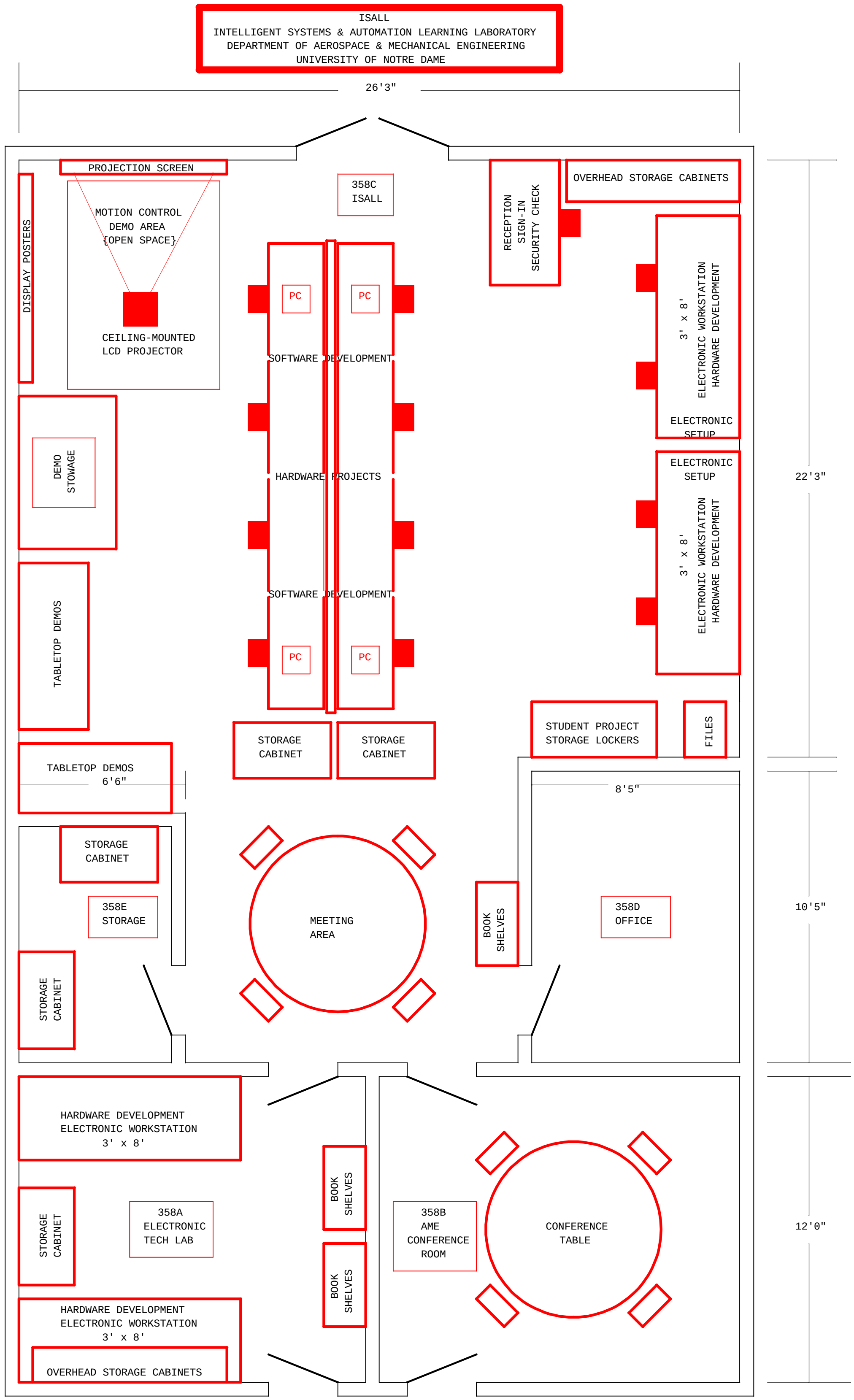

Figure 11. Intelligent Systems and Automation Learning Laboratory.