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A Multi-Disciplinary Mechatronics Course with Assessment—Integrating Theory and Application through Laboratory Activities*

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The mechatronics course for undergraduate and graduate level engineering students, a technical elective offered by the Department of Mechanical Engineering at Clemson University, promotes the exploration of mechatronic system integration concepts. The course objectives are to create a collaborative environment for the multi-disciplinary engineering students, provide hands-on experience with mechatronic systems, develop teamwork, leadership, and project management skills, and prepare the students for current industry standards. The holistic course activities include studying fundamental knowledge from mechanical, electrical, computer, industrial, and robotics engineering, which is re-enforced through laboratory experiments and semester long projects. The design projects foster collaborative teamwork activities and offer the opportunity for in-depth experience with sensors, actuators, and material handling systems. The course assessment, which establishes a basis for continuous improvement, considers student performances, their written feedback on qualitative surveys, and feedback offered by an advisory panel composed of industry experts and faculty members. The assessment methods evaluate the performance of students and the course to further improve the overall learning experience. Past evaluation results have shown that the students consistently improved in four learning goals and the advisory panel offered favorable remarks about the course.

Keywords: mechatronics; classroom concepts; laboratory experiments; design projects and assessment

1. Introduction

Mechatronics is the integration of mechanical, electrical, computer, industrial, and robotics engineering concepts in the design of smart products and processes. As the size and cost of digital hardware and sensing technology decreases, more mechatronic systems are being used in industries such as aerospace, defense, health care, material handling, and transportation, as well as consumer products including kitchen and laundry appliances, garden/lawn care, and entertainment. To design mechatronic systems and smart products, engineering students must acquire necessary skills and practical experience. Specifically, they should be able to apply electronic circuits, sensors, actuators, microprocessors, control theory, and systems integration so that diverse technologies can be combined to realize a functional product. A multi-disciplinary mechatronic course for undergraduate/graduate students at Clemson University has been developed to address the needs of engineering students and industries. This course integrates fundamental concepts with hands-on experiences during laboratory activities and design projects.

Students generally learn and retain more knowledge when they experience or practice what they have learned [1]. The design of a multi-disciplinary mechatronics course with laboratory component is well suited for this learning approach, since students receive extensive opportunities to practice and explore concepts. They participate in dynamic team interactions to apply knowledge gained from past courses and investigate real ideas to solve assigned problems. Diong et al. [2] described a similar approach used at the University of Texas at El Paso for a mechatronics course. The assessment analysis and results indicated that the hands-on mechatronic projects had improved student learning in control systems. Ramasubramanian et al. [3] reported on a graduate level multi-disciplinary course in mechatronics at North Carolina State University for electrical and mechanical engineering students. Smaili and Chehade [4] discussed the efforts made by the American University of Beirut to offer a mechatronics course that emphasized just-in-time learning, projects, learning-by-doing, and minimal lecturing. Guerra-Zubiaga et al. [5] developed a senior level mechatronic course at ITESM of Tecnológico de Monterrey where students used design methodology concepts to realize design requirements of a selected manufacturing company.

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Kurfess [6] presented the challenges and lessons learned while integrating a new mechatronics course into a large second-year design course at Georgia Tech. He reported on the different devices used for the course project and their relative costs. Yavuz and Mistikoglu [7] described a study to determine whether to create a separate mechatronics department at Mustafa Kemal University. An interesting aspect of the article was the discussion of the approaches by global universities to offer mechatronic courses. Gupta et al. [8] presented a mechatronics syllabus designed for undergraduate students at Malaviya Regional Engineering College, which consisted of eight semesters. They documented the necessary laboratory equipment, commercial software, and other requirements for the course.

Krishnan et al. [9] designed two mechatronics courses at the University of Detroit Mercy entitled "Modeling & Simulation of Mechatronic System," and "Sensors & Actuators for Mechatronic Systems." Rogers et al. [10] at the United States Military Academy offered a mechatronic course to solve open-ended problems in interdisciplinary fields and provided course assessment results. Grimheden [11] described a mechatronics course designed at the Royal Institute of Technology that involved international collaboration projects with universities from Australia, Europe, Japan and the United States. Uelschen et al. [12] described an introductory course on software engineering for undergraduate mechatronic students that focused on goal-orientation and pragmatic problem solving at the University of Applied Sciences Osnabrück. Solis et al. [13] presented an introductory mechatronic course for undergraduate students using robotic systems at Waseda University. The authors adopted a Project Based Learning (PBL) model to introduce the laboratories and undertake an inverted pendulum-based robotics competition. Finally, Rojko et al. [14] conducted a mechatronics e-course for both traditional students and industry professionals with classical and remote laboratory experiences using an adaptable learning approach. Overall, these efforts indicated a growing need to prepare students for multi-disciplinary work assignments subject to rapidly changing industrial environments. The mechatronic courses offered at these institutions typically used laboratory settings and well-designed course work. However, the development of project management, human factors and people skills within the students, the supply of current industrial material handling hardware, sensors, actuators, and data acquisition systems, collaboration of different engineering discipline faculty, and course assessments by industry experts offer a unique learning environment at Clemson University.

The mechatronics course at Clemson University has been offered since 2001 and covers the traditional areas of mechanical, electrical, computer, and industrial engineering. The unique features of this course are the hand-on experiences with Programmable Logic Controller (PLC) programming for stand-alone and networked applications, an industrial Staubli robotic arm featuring sensor feedback, and material handling (conveyor) systems. It also includes the use of breadboards for electronic circuits, as well as various electrical machines, sensors, actuators, and data acquisition systems common to the workplace. Apart from this, the course includes people skills such as business ethics, leadership, team building, collaboration, and human factors. To understand the relevant materials, the students meet twice per week in a classroom and have an accompanying weekly laboratory session to experience mechatronic systems. From Fall 2008 to Spring 2011, this course had been offered four times. Enrollment data showed that the majority of students were mechanical engineering majors. The evaluation results for this period indicate that the course has received very positive responses from students (refer to Section 3). As part of a continuous improvement process, an industry advisory panel has been formed to work with the teaching faculty in analyzing the progress of the overall course activities. The course objectives are to provide a collaborative environment for multi-disciplinary engineering students, practical experience with mechatronic systems, develop student leadership and project management skills, and embrace industry technology through laboratory assignments. Overall, the course novelty arises from extensive multi-disciplinary faculty collaboration: to develop the course materials, performance assessment of the students, improvement in the laboratory experiment offerings by utilizing student designed projects, encouragement of students to demonstrate their leadership and people skills through the mechatronic system projects, and visit to industry plants which extensively utilize mechatronic systems.

This paper describes a mechatronics course offered at Clemson and the accompanying assessment process. Some of the key course features include integrated classroom and laboratory teaching, design projects, and emphasis on people skills. The manuscript is organized as follows. Section 2 reviews the classroom, laboratory, team design project activities, and industrial plant tours that establish the basis for learning. Sections 3 and 4 contain the assessment methods, assessment data, and accompanying discussion about the results that reflect the successful course development. The conclusion is presented in Section 5.

2. Student learning methods in the mechatronics course

The student learning strategies emphasize hands-on laboratory experiences using current technology, design projects, and collaborative classroom activities. The laboratory experiments and team based design projects require students to integrate sensors, actuators, and computer control into electromechanical systems. The classroom teaching efforts incorporate these technical concepts with people and business skills in a peer setting. Students learn and practice those lessons in both the classroom and the laboratory assignments. The application of mechatronic systems are best illustrated by industrial plant visits to companies located within a 50 mile radius of the university. Collectively, the classroom activities, experiments, projects, and plant tours are designed to emphasize systems integration, a team approach, and to showcase practical applications. These methods will be explained in the following subsections.

2.1 Classroom activities

The classroom activities encourage independent student readings, in-class discussions, and laboratory explorations. The short lessons and accompanying discussions focus on various topics within mechanical, electrical, computer, and industrial engineering, plus systems integration as listed in Fig. 1. A special aspect of the course is the emphasis on people skills, including collaborative learning, project management, team building, leadership development, ethics, procurement, and writing design specifications. Students are assigned to multi-disciplinary teams that collaborate towards completing design projects. One of the course objectives is to organize students of different backgrounds together for learning a common platform, namely mechatronic systems.

The classroom activities also involve solving in-class examples, which allow students to practice recently learned course material. These examples help to develop a collaborative approach towards problem solving and team building. Students learn to respect and share ideas reflecting different points of view. Weekly assignments on course material are given to students for an in-depth understanding of subject areas such as state–space representation, use of operational amplifiers, hydraulic and pneumatic circuit design, data acquisition, derivation of transfer functions for electro-mechanical systems, etc. Homework assignments include problems based on the conceptual design and PLC programming for mechatronic systems (e.g. automatic car wash, bank ATM machines, railway crossing systems, etc.). During classroom sessions, different mechatronic devices, such as electronically controlled hydraulic and pneumatic valves, photo-electric switches, proximity sensors, accelerometers, and electronic fuel injectors, are inspected by students to view the practical applications of mechatronic devices. Students are also required to demonstrate continual progress on their design projects by presenting activities related to various sensors, actuators, project planning, cost estimates, and team accomplishments.

2.2 Laboratory experiments

The laboratory experiments have been designed and created by students enrolled in past course offerings to offer hands-on experiences of electrical, hydraulic, mechanical, and pneumatic systems. The laboratory is scheduled for three hours weekly for student

Mechanical Engineering - Actuators - Hydraulic Systems - Mechanical Systems - Pneumatic Systems - Sensors - Thermal Systems	**Electrical Engineering** - Amplifiers - Circuits - Data Acquisition - Electric Power - Electronics - Electric Motors	**Controls Engineering** - Block diagram - Control Systems - Robotic Systems - State Space - Transient Response	**People Skills** - Collaborative Learning - Project Management - Team Building - Leadership - Ethics - Procurement & Specifications
Computer Engineering - Digital Logic - Matlab / Simulink - PLC Algorithms - Robot Arm Commands	**Industrial Engineering** - Human Factors - Human / Machine Interface - Safety - Workers	**Systems Integration** - System Design - Case Study of Integrated Material Handling System	

Fig. 1. The various mechatronic system classroom topics covered during a semester.

teams of 3–4 individuals per station. A laboratory manual [15] that describes the laboratory experiments is provided to guide students when conducting the experiments and to focus their attention on the learning objectives. Figure 2 provides a list of the experimental topics covered during the laboratory sessions. A variety of different software packages such as LabVIEW, Matlab/Simulink, RS Logix 500, and Solid Works are used for these investigations. Students learn to integrate different sensors, actuators, hardware, and software into the experiments, which offer challenging hands-on experiences. These endeavors prepare students to better serve industry needs.

As part of the laboratory experiments, the teams are required to integrate two PLCs with a Staubli robot to complete process cycles. Students create software programs for the robot to perform ''pick and place'' operations to assemble a connecting rod, piston, and wrist pin on a fixture. After this activity, the assembly must be transported on a conveyor system from one location to another with the help of proximity sensors. To coordinate the robot movements, the students are required to store robot arm positions using the teaching pendent. These stored positions are sequentially retrieved in the robot program. Once students successfully complete this task, they are requested to integrate the conveyor system controlled by two networked PLCs. The first PLC coordinates information with the Staubli robot, while the second PLC collects conveyor operational data, including the part color, barcode number on the storage box, and storage box progression along the conveyor. Since the two PLCs are networked together, they share this information to perform different operations according to the loaded ladder logic written in the PLC program. In the next laboratory session, students have to combine earlier explained laboratory session activities to integrate the robot arm movements with PLC program commands. It has been observed that the students enjoy working on robot programming and coordinating it with the PLCs to complete different processes. This enthusiasm was helpful to promote engagement for student learning, persistence, and success. Students also suggested increasing their laboratory session duration time so that they could undertake more experiments.

2.3 Team based design projects

Team based design projects have been introduced to encourage students to synthesize the classroom and laboratory concepts throughout the semester by focusing on a single comprehensive engineering challenge in the design of a mechatronic system. Students need to apply the knowledge they gained in the classroom and laboratory to complete their design projects as shown in Fig. 2. The design projects require critical thinking by students while working on collaborative design tasks, project planning, team management, and material procurement. The students also need to complete documentation for their project, which is often neglected in the workplace. Further, Clemson University is committed to ''writing across the curriculum'' to improve students' technical communication skills. To develop leadership skills among students, team leaders are selected by each team to guide their efforts. The team leader has the responsibility of coordinating the different tasks for the project, communicating with the course instructor and laboratory teaching assistant, and ensuring completion of the project within the given time period. Weekly meetings of the team leaders with the instructor are necessary to complete the projects within a semester. Every team is required to evaluate different sensors, actuators, and electronic devices that may need to be purchased. The teams subse-

No.	Experiment name
1	Electronic dice circuit
2	Rotation counter circuit
3	Introduction to ladder logic
4	Allen Bradley PLCs & RSLogix500
5	Traffic light experiment
6	Introduction to Staubli robot arm
7	Staubli robot arm & integrated PLCs
8	Control of pneumatic actuator
9	Conveyor material handling system
10	Torsional & swinging pendulums

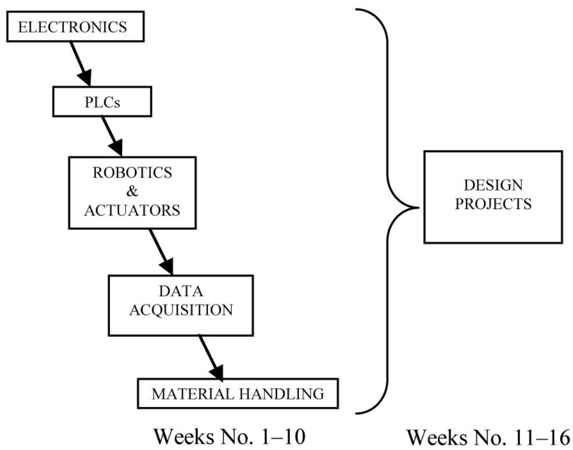

Fig. 2. Mechatronics laboratory activities and associated time frame.

quently submit procurement requests to the instructor. Progress update presentations are given in class during the semester. The following list of projects show the contributions made by the student design projects to the mechatronics laboratory experiments [16, 17]. Some of the student design projects are shown in Fig. 3.

- *Conveyor System Design*: Students designed a modular conveyor system with individual smart rollers and assorted sensors to operate under networked PLCs control.
- *Hydraulic and Pneumatic System Integration*: Using National Instruments hardware and software for data acquisition, students integrated hydraulic and pneumatic components together to perform assigned tasks.
- *Library of Electronic Circuits*: Different types of small electronic circuits were developed using breadboards. Some of these electronic circuits, including the electronic dice and rotation counter, are mentioned in Fig. 2.
- *Staubli Robot Programming*: Students developed programs for the robot to pick and place objects and transport them on the conveyor system. They developed programs to coordinate the Staubli robot with the PLCs to start and stop the conveyors when required.

2.4 Plant tours showcasing manufacturing technologies

The plant tour is an important aspect of this mechatronic course and provides the students an opportunity to view and understand mechatronic system applications in manufacturing environments. The students view different sensors, actuators, robotic assemblies, PLC controlled systems, product assembly lines, automated part storage and transport systems, testing facilities, etc. Further, they can directly observe the applications of human factors, and human–machine interactions. For many students who haven't toured a plant before, these trips offer motivation to consider working in the mechatronics field. Instructors and students have toured industrial companies such as BMW Assembly Plant (Greer, SC), Michelin Tire Plant (Sandy Springs, SC), Bad Creek Pumped Storage Station (Salem, SC), Duke Oconee Nuclear Power Plant (Seneca, SC), Santee Cooper (Abbey-

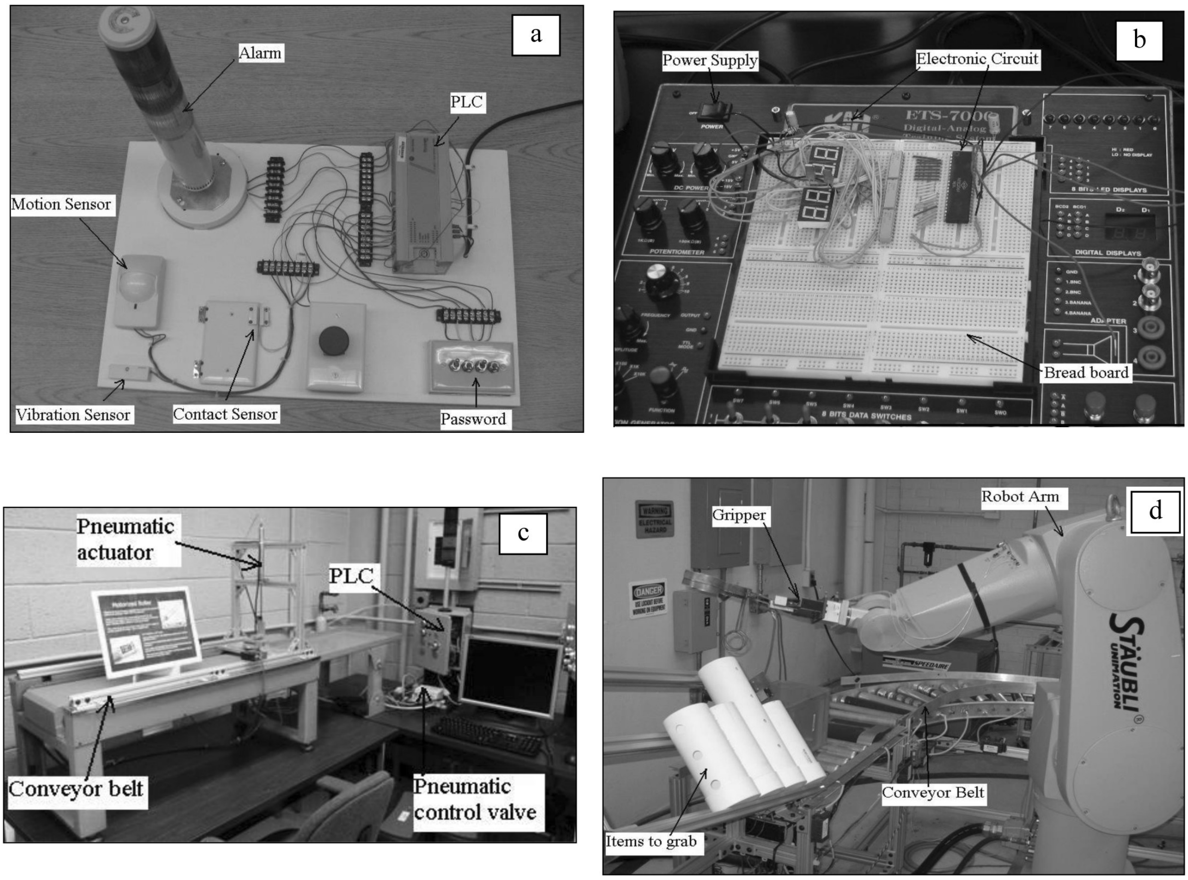

Fig. 3. Assortment of past and present mechatronics laboratory experiments: (a) security system with the PLC, (b) breadboard electronic circuit with timing chip and digital display, (c) bench top conveyor belt system with pneumatic actuation, and (d) Staubli robot arm with part pick and place operation.

ville, SC), and Advanced Automation (Greenville, SC). Students learn the importance of project planning, leadership skills, integration of different mechatronic systems, clear communication between project team members, and the necessity of multidisciplinary study.

3. Course evaluation using assessment data

The assessment for this mechatronic course has been performed in three ways, to evaluate student learning and course structure. The first assessment method is called Pre-Test and Post-Test, where data gathered before implementation of an activity (starting of the course) and after implementation of an activity (at the end of the course) are compared to determine the outcome changes. The second method is Qualitative Assessment, where the opinion of a person (i.e., student) who has just performed an activity is recorded to evaluate the task effect. The last assessment method is the collection of feedback from a Technical Advisory Panel, which contains industry experts and faculty members to evaluate the progress of the mechatronic course. Together, the assessment data provides the analysis to take necessary actions for improving the course.

3.1 Pre and post-course test results

The pre/post-test is designed to assess the knowledge gained from classroom activities and assignments. It has twenty-one items assessing mechatronic systems, collaborative learning, and team building methodologies. Results from the questions are presented on a 5 point scale from 1, indicating not correct, to 5, indicating completely accurate. Table 1 shows the four learning goals. Personal growth targets individual knowledge gained by the student, team building focuses on team performance, mechanics/engineering targets specific engineering disciplines such as controls, electronics, and mechanics for student's knowledge gain, and human factors focuses on the industrial work perspective gained by students. The results in Table 1 show that there has been growth in the performance of students over each semester. The pre-test scores indicate that students enrolling in the course were deficient in the four learning goals. The post-test scores indicate that students performed well in the mechatronics course after going through the classroom and laboratory activities. The standard deviations (SD) for the post-tests are observed to be low, which indicates that most students have gained knowledge through the mechatronic course over the period of time.

To validate the pre-test and post-test statistics, a within-subjects or repeated measures approach has been selected. This research project calculated the 'F' scores as the ratio of two variances that were calculated in Table 1 for four parameters (learning goals). The respective 'F' scores are listed in Table 2; the data show that the student's knowledge of the course material had improved. The largest increase in knowledge was observed for Mechanics/Engineering. There was a significant increase ($p < 0.05$) in the knowledge of students for each of the four learning goals when the post-test results are compared with the pre-test results.

3.2 Qualitative assessment by students

The qualitative assessment of the course was completed by assessing student feedback to supplement

Table 1. Pre-test and post-test means and standard deviations (SD) for four semesters

Learning goal		**Personal growth**	**Team building**	**Mechanics/ Engineering**	**Human factors**
Fall 2008	Pre-test mean (SD)	3.23 (0.50)	4.34 (0.41)	2.89 (0.85)	3.38 (1.71)
	Post-test mean (SD)	3.60 (0.52)	5.00 (0.00)	4.61 (0.23)	4.92 (0.28)
Fall 2009	Pre-test mean (SD)	2.99 (0.42)	3.88 (0.75)	2.38 (0.72)	4.05 (1.62)
	Post-test mean (SD)	3.57 (0.46)	4.73 (0.36)	3.78 (0.52)	4.68 (0.95)
Spring 2010	Pre-test mean (SD)	3.18 (0.52)	4.03 (0.77)	2.56 (0.79)	3.74 (1.63)
	Post-test mean (SD)	3.39 (0.51)	4.68 (0.44)	3.64 (0.51)	4.52 (1.2)
Spring 2011	Pre-test mean (SD)	3.52 (0.48)	4.03 (0.51)	2.66 (0.66)	4.56 (1.28)
	Post-test mean (SD)	3.77 (0.38)	4.44 (0.48)	3.52 (0.53)	5.00 (0.00)

Table 2. Quantitative student learning data for four semesters with 'F' scores and accompanying '*p*' levels

Learning goal	**Personal growth**	**Team building**	**Mechanics/Engineering**	**Human factors**
	F (*p*)	F (*p*)	F (*p*)	F (*p*)
Fall 2008	8.35 (0.014)	33.62 (0.000)	65.23 (0.000)	11.82 (0.005)
Fall 2009	24.77 (0.000)	29.50 (0.000)	140.61 (0.000)	3.40 (0.080)
Spring 2010	6.98 (0.015)	14.68 (0.001)	48.18 (0.000)	7.39 (0.013)
Spring 2011	8.54 (0.002)	15.79 (0.001)	55.82 (0.000)	3.27 (0.083)

the quantitative assessment results. In the qualitative assessment, students were asked about what they liked in the course, the instruction methods, and their recommendations for the future offerings of the mechatronic systems course. Similar to the previous assessment, the qualitative assessment was completed near the beginning of the semester and at the conclusion of the course to evaluate student perceptions regarding the mechatronic course as a whole. Table 3 lists the student likes, dislikes, and recommendations for the pre- and post-qualitative assessments. Students generally liked the hands-on approach to learning and suggested adding extra sample problems in the notes to help them solve the home work problems. However, several students disliked the workload or difficulty level of the course.

3.3 Technical advisory panel observations

The Technical Advisory Panel (TAP) consists of the NSF (National Science Foundation) grant investigators, external industry experts, and selected faculty members. The TAP assesses the overall learning objectives of the mechatronic course, the progress of students, academic course material improvements, actual applications of student projects, future laboratory equipment requirements, possible industry equipment donations for academic purpose, software license requirements, etc. As part of the TAP assessment process, students present their completed projects to the TAP to demonstrate their knowledge and their approach to achieve the team objectives for their projects. Along with the student presentations, faculty members present the pre- and post-assessment data, progress made by students, and difficulties of students and faculty in delivering the classroom materials and laboratory experiments. Some of the most challenging aspects of the mechatronics laboratory include software license renewals, new software and hardware procurements, proper maintenance of equipment, and industry sponsors. The TAP suggestions included attention to practical issues in the workplace while completing the projects, and improvements in the laboratory. The observations and comments of the TAP are presented in Table 4.

Table 3. Qualitative student comments

Assessment	Student likes	Student dislikes	Suggested changes
Pre-	• Class notes are clear and informative • Instructor has a good understanding of the material • Use of pictures/videos of related topics • Hands-on approach and interaction is helpful • Discussion of real-life applications • Potential for plant/factory visits • Instructor enthusiasm for the material • Course merges different areas of engineering • Interactive • Course keeps attention and focus is well-structured	• Material goes too fast • Complexity of the some material • Homework difficulty • Not all topics received adequate attention • Not enough examples in class • Class time too short • Projects are intimidating and extensive, like a capstone project	• Cover less material in more depth • Spend more time on the notes • Slower communication • More in-depth talk about the homework • Work through more examples • Stress the important topics
Post-	• Lab goes well with class • Instructor has a lot of energy, which makes the class exciting • Hands-on application of the systems in the lab and field trip • Good class notes • Real-life examples • Good communication skills • Interesting discussions • In-class problems • "Show and Tell" with mechatronic components • Appropriate material level of background • Availability of instructor • Teaching style and willingness to help • Homework assesses knowledge/ understanding	• Homework does not assess knowledge—not connected to the class material • Project is time-consuming • More examples • Difficulty of the homework • Pages in the notes aren't numbered • A lot of information to learn • More instruction on what to expect on tests	

Table 4. Comments from Technical Advisory Panel (TAP)

Laboratory design project	Miscellaneous feedback
• Suggested improvements to HMI (human–machine interface) – process information, status bits, sensor status, number of parts processed, number of parts rejected, operating time, some robot information displayed • Write on text terminal in V++, network resource (Allen Bradley HMI; Factory Talk); ethernet connection for PC version of Factory Talk; programming client, RSView 32, HMI platform - RSLogix 5000	• Vision system with dice, ProE software to implement, simulation studies, robot works • "Done a good job, lots going on in a semester. Real challenge to find things to suggest" • "Team and project important aspects" (of this mechatronics course) • Recognized improvements to these courses at Clemson University and Greenville Technical College during the grant's four-year time period • Realistic design projects are offered which would be encountered in industry • Researchers have taken panel's suggestions and comments to improve the courses • Go ahead for NSF Phase II proposal to partner with regional/ national schools and companies

Apart from the assessment by the TAP, the faculty also consults with industry experts to further resolve laboratory issues.

The course has undergone continuous improvements based on the analysis of all the assessment results, student feedback, and TAP suggestions. The course has benefited by including new engineering topics in the course syllabus, interactions with students about the in-class problems, industrial software and hardware training for students to complete their design projects, and inclusion of new student projects to upgrade the laboratory experiments and student's laboratory manual.

4. Discussion

The mechatronics course assessment results of the pre- and post-tests for a four course offering period from 2008 to 2011 show that improvement occurred in the performance of the four student learning goals. Specifically, an average improvement of 7% for personal growth, 12.8% for team building, 25.4% for mechanics/engineering and 17% for human factors has been noticed in the post-tests for students over pre-tests. The advisory panel also offered positive remarks about the course development indicating that a successful learning environment has been achieved.

5. Conclusion

The prevalence of mechatronics systems in manufacturing processes, consumer products, and a host of other engineered items have increased the need for universities to offer mechatronic courses. The mechatronics course at Clemson University builds upon best practices for class room instruction, laboratory experiments designed by the students, and semester long projects to synthesize the mechatronic concepts. In this paper, the learning activities and assessment methods used in the technical elective course have been presented and discussed. As part of the teaching methods, the classroom activities focus on fundamental engineering concepts, while the laboratory tasks offer hands-on experiences with sensors, actuators, and different mechatronic systems. Semester long design projects prepare students to acquire critical people skills such as leadership, project management, and collaborative approaches while designing prototype mechatronic systems. The industrial plant tours offer students first-hand insight into manufacturing facilities. The analysis of the course assessment data and feedback from the students plus Technical Advisory Panel show that the mechatronic course has been truly practical and effective in delivering the knowledge about mechatronic systems.

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