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A Laboratory Designed to Enhance Students' Interest in and Learning of Controls*

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A state-of-the-art mechatronics laboratory, for use by both electrical engineering and mechanical engineering students, was recently developed at The University of Texas at El Paso through the assistance of the US National Science Foundation. This initiative was aimed at enhancing student interest and learning via a model-based, simulation-oriented approach to control systems analysis, design and development, culminating in the implementation of a digital signal processor-based controller for an inverted pendulum system. This paper describes the laboratory's development, its associated equipment and experiments, and provides details regarding project evaluation and its results that indicate the laboratory's positive impact on student interest in and learning of the controls subject.

INTRODUCTION

THE UNIVERSITY OF TEXAS at El Paso (UTEP) is a comprehensive four-year public institution with an engineering student population that is currently about 70% underrepresented minority. A significant majority of UTEP's engineering students are also first generation college attendees from humble backgrounds: many of them work at least part-time to support themselves and their families. Compounding the challenge of educating such students is a liberal admission policy that has resulted in classes with students spanning a wide range of ability and preparation. Many of the less able and less well-prepared students show a lack of confidence in their abilities and find it difficult to relate lecture material to real-world problems, especially in courses that tend to be more mathematically intensive. On the other hand, they appear more motivated and do better in our existing laboratory courses and in courses that use computers more intensively, i.e., they enjoy hands-on experience and learn better that way. This observation basically reinforces the conclusions of prior research such as [1], suggesting that people learn and retain much more of what they experience directly or practice doing than what they only hear and/or see.

Outside the classroom, changes have been occurring over the past decade that provide additional motivation for modifying the way certain classes, such as Controls, are taught. The most significant is the need of industry, in the face of global competition and shortening product cycles, for engineering graduates to be more interdisciplinary in their thinking and to have a broader range of skills [2], so as to increase their productivity. Regarding the Controls discipline, there appears to be a growing demand for more and more engineered systems (for businesses and for consumers) to rely on control systems that are electronic, embedded and also digital in nature; the latter having the significant advantage of being easily programmable to yield improved product functionality.

It was against this backdrop of internal and external factors that a decision was made to add a Controls laboratory course to the UTEP Electrical Engineering (EE) curriculum to help stimulate the students' interest, boost their self-confidence, improve their understanding of the lecture material and prepare them better for the present needs of industry. While it would have required little effort to simply model this new course after the existing Controls laboratory course being offered by UTEP's Mechanical Engineering (ME) department, the available equipment and experiments for this existing course badly needed updating. Then due to the funding constraint on one hand, which provided substantial motivation to maximize resource utilization (space and equipment), along with the goal of fostering an interdisciplinary environment on the other hand, the EE and ME departments ultimately decided to jointly plan for one new Mechatronics Laboratory.

In the following, we first briefly describe the laboratory's development (objectives, equipment and operation) and then detail the project's evaluation and the conclusions obtained. We include the lab description in this paper, even though the concept of a DSP board-based mechatronics facility is no longer the novelty it was in 1995 when the

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first author began working on such a lab, so it can serve as a complete archival account of this project. On the other hand, the evaluation description and its results represent this paper's original contribution since other developers' of similar labs such as [3–5] make no mention of evaluating their lab development projects; while [6] mentions using student questionnaires for evaluation purposes and presents a few student remarks, it does not describe any quantitative analysis of their responses.

In addition, to place this paper in its proper context, brief descriptions of the EE and ME Controls (lecture) classes currently being taught at UTEP and the previously taught ME Controls laboratory class are provided in the Appendix.

OBJECTIVES OF THE NEW MECHATRONICS LAB

Recent efforts to set up similar labs were consulted [3–5] before we adopted the set of desired objectives for this new lab. This planning also benefited from the experience of the first author who conceived of and began developing a similar lab in 1995 [7] while he was a faculty member at another university. The present lab represents an update of the original concept with certain modifications suggested by this previous experience. It also shares some objectives with the lab described in [3] including comprehensive hardware exposure and a strong cross-disciplinary emphasis. Also certain experiments are similar such as system identification (from Bode plots) and step responses with PID controller variation, and include comparisons of practical versus ideal component behavior. However, the main drawback of the package of experiments described in [3] lies in the lack of flexibility of the controller structure so most students may find it difficult to generalize from that. In [4], the authors described the use of microcontrollers for the experiments, which however required students to be introduced to C programming during the lab course. As for [5], while it also used more flexible, programmable controller hardware and software, the lab was clearly aimed more at graduate students and research training instead of undergraduate education.

Subsequently, we submitted a proposal to the US National Science Foundation's Course, Curriculum and Laboratory Improvement Program [8] for the establishment of a state-of-the-art mechatronics instructional laboratory at UTEP. The proposal was funded, this laboratory was developed and it is now being used by both electrical and mechanical engineering undergraduate students at UTEP. Its main objectives are to:

1. Stimulate students' interest in, and improve their understanding of, the Controls subject.
2. Familiarize students with a model-based simulation-oriented approach to control systems design and development.
3. Prepare students to be more multidisciplinary in their thinking.
4. Let students gain experience with 'real-world' software and hardware needed to implement digital signal processor (DSP)-based controllers.
5. Enable students to demonstrate their implemented controllers on a non-trivial electromechanical system.

Note that the last two objectives distinguish this project from those that allow students to experiment with 'canned' analog or even DSP-based controllers but do not let them gain an understanding of, and hands-on experience with, the final implementation step in the control design and development process. Such an omission, we feel, results in a less than adequate preparation of today's Controls student. Moreover, the cost and effort of taking students that one step further is decreasing as less expensive, more powerful, and easier to use DSPs and their development tools come on the market.

DESIRED LAB COURSE OUTCOMES

The next step taken was the design of a set of experiments for the new/revised common lab course that support the above-mentioned objectives. These would focus on the following key topics:

- state equation and transfer function modeling;
- time domain (steady-state and transient) performance;
- Bode plots for system identification and stability analysis;
- introduction to a DSP development system for controller implementation;
- evaluation of PID and state feedback controllers for the inverted pendulum system (in default configuration);
- modeling, analysis, control design, simulation and DSP controller implementation for the inverted pendulum system (configured differently from above).

The resulting eight experiments are summarized in Table 1.

Note that Labs 7 and 8 each stretches over two weeks. These experiments in turn served to guide our selection of the hardware and software needed for this laboratory.

SELECTION OF LABORATORY HARDWARE AND SOFTWARE

The key requirement driving the hardware and software selection process for this new lab was to realize an open, integrated controller development

Table 1. The set of experiments for the new Mechatronics Lab course

Lab	Topic	Specific features
1	Modeling of dynamic systems	Introduction to Matlab State and output equation modeling Transfer function modeling
2	Modeling of dynamic systems	State and output equation modeling Transfer function modeling
3	Time-domain performance	Steady-state error Underdamped, critically damped and overdamped responses Step response solution via inverse Laplace transform
4	Dynamic signal analyzers: Bode plot and system identification	Introduction to frequency response measurement methods and use of curve fit algorithms to identify system transfer functions
5	Frequency response	Comparison of ideal and measured frequency responses Stability margins
6	Introduction to DSP development system and control implementation	The different components (hardware and software) The development and implementation process
7	Modeling, analysis, control design, simulation and DSP control of the Inverted Pendulum system (using ECP h/w & s/w)	Obtain PD controller gains that will satisfy the given design specifications and demonstrate proper control of the actual system
8	Modeling, analysis, control design, simulation and DSP controller implementation for the Inverted Pendulum system (using dSPACE h/w & s/w)	Implement a state feedback controller that satisfies the given design specifications and demonstrate on the actual system

platform that allows plant modeling, analysis, control design, system simulation, controller implementation and control verification, encompassing the entire spectrum of required control design and development activities. Such a platform has emerged recently because of the tremendous performance gains in digital computing technology and a simultaneous reduction in its cost. Furthermore, its adoption by industry has increased steadily as reducing product development time and cost, which this technology facilitates, become more pressing concerns in an increasingly competitive global marketplace. Hence, we believe that the new UTEP Mechatronics Laboratory can not only serve as a means of education but also as a place of training to prepare our students to quickly contribute effectively to their new employers.

Presently, the laboratory is equipped with the following items:

- Matlab, Control System and Symbolic Math toolboxes, Simulink and Real-Time Workshop software;
- DSP development software and hardware boards with analog outputs, suitable for driving DC motors;
- dual-channel dynamic signal analyzers/function generators /oscilloscopes;
- electronic and electromechanical systems, to be controlled.

Matlab®, a product of The MathWorks Inc. [9], represents the software platform underpinning the function and usage of all other equipment in the laboratory. It interfaces with a measurement and analysis module (described below) to provide visualization of the data acquired by that module. It is also used for system modeling, analysis, control design, simulation, and to provide an interface to a DSP control development system (also described below). This latter feature allows one to assemble a model of the control algorithm using graphical modules, generate C code from that model, which is then compiled into processor-specific code for download to the DSP. An additional advantage is that the software is available, for educational purposes, at a substantial discount. The alternatives to Matlab we considered were Wind River Systems' (previously ISI's) MATRIX_X® and Boeing's EASY5®; however these are not as widely adopted or as broadly supported by third-parties as Matlab is.

The DSP development system is the other key piece of equipment in this new laboratory. Its function is to generate processor-specific code implementing the desired control algorithms for the plant systems, download the program to the DSP, and provide the physical control signals (during active operation) for actuating those plants. When compared with similar systems, the TMS320C31 DSP-based DS1102 system from dSPACE Inc. [10] was found to be the most suitable from both the cost and functionality standpoints (although it has now been superseded by the DS1104).

The equipment in the laboratory also includes the SigLab 20–22 measurement and analysis module from the MTS Systems Corporation's DSP Technology division [11] which, with the aid of Matlab, implements the following instruments with graphical user interfaces: oscilloscope, function generator, swept-sine analyzer, etc. It provides all of the basic measurement and signal generation functions required for this laboratory in a single, small, portable and inexpensive package. While other monolithic-type instruments were considered, for example the HP 35670A dynamic signal analyzer, they were considered too expensive to

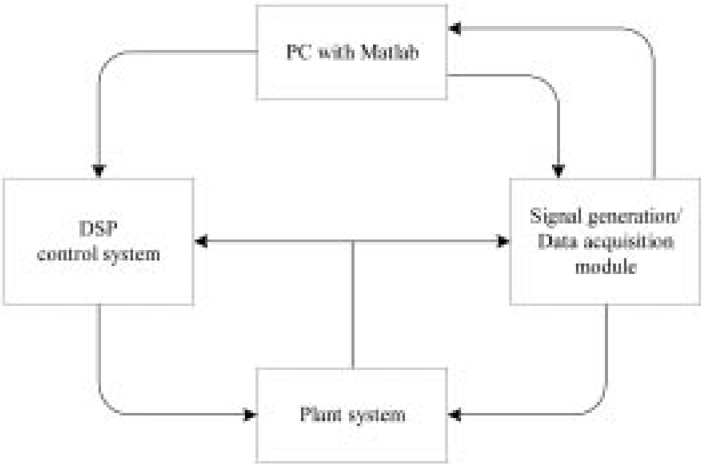

Fig. 1. Mechatronics Laboratory experiment station configuration.

have one each per laboratory station and had substantial capabilities that would rarely be utilized in an undergraduate laboratory, and so were dropped from consideration.

Various electromechanical plant systems were evaluated. The candidate vendors included Feedback Inc., Quanser Consulting and Educational Control Products (ECP) [12]. The systems need to be easy and robust enough for the students to work with yet present fairly challenging control problems with clearly visible results. We finally selected the ECP Inverted Pendulum system as the main plant system for this laboratory as it satisfies all of the above requirements. We considered, but decided against, ordering these systems with their own proprietary control software. This is because, as previously mentioned, a major objective of this proposed lab is to have the students learn how to implement a prototype DSP controller as part of an integrated design and development process rather than simply adjust the parameters of 'canned' controllers.

To run the described software and hardware in this laboratory are 10 Pentium III PCs that were donated by the Hewlett-Packard Foundation. A network server and a color inkjet printer, also donated by that Foundation, round out the list of equipment presently available in this lab.

Figure 1 shows a diagram of the equipment configuration for each station in this laboratory, while Fig. 2 shows a picture of a workstation in this lab being used for an experiment.

LABORATORY DEVELOPMENT AND OPERATION

The initial focus of this laboratory's development was to make it ready for a few key demonstrations of its capabilities. By Summer 2000, the procedure for the frequency domain measurement and system identification experiment (on an RLC circuit) had been completed and a demonstration conducted for the Fall 2000 class of ME Controls students. In addition, control algorithms for balancing the inverted pendulum were successfully developed and implemented on the dSPACE DSP platform, and then demonstrated for the Fall 2000

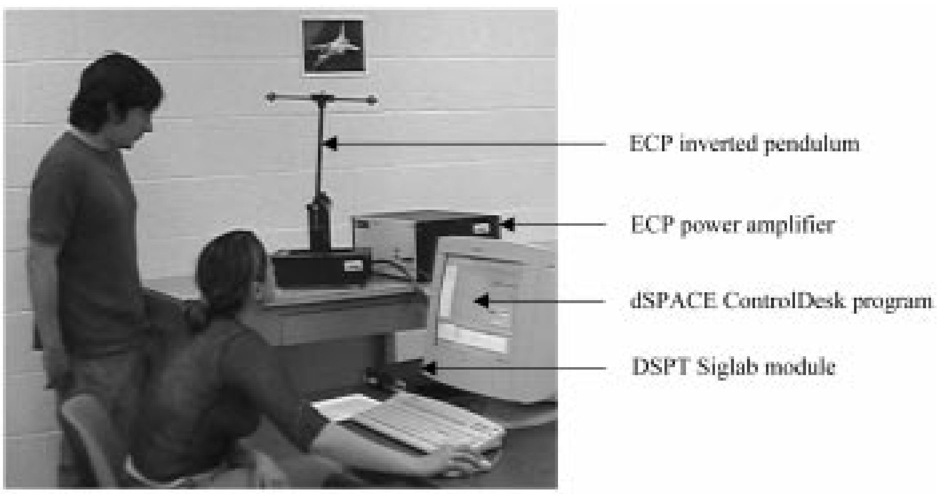

Fig. 2. Mechatronics Laboratory experiment station.

Table 2. Results of students' self-assessment of *interest* in controls

	EE Spr2000 Control Pre	EE Spr2000 Control Post	EE Spr2000 Control Diff	ME Spr2000 Control Pre	ME Spr2000 Control Post	ME Spr2000 Control Diff	EE Spr2001 Pre	EE Spr2001 Post	EE Spr2001 Diff	EE Spr2002 Pre	EE Spr2002 Post	EE Spr2002 Diff	ME Fall2002 Pre	ME Fall2002 Post	ME Fall2002 Diff
Attending controls lectures	3.44	3.73	0.28	3.20	3.40	0.20	3.80	4.80	1.00	2.93	3.86	0.93	3.88	3.82	−0.06
Attending controls labs	2.75	3.00	0.25	2.80	2.20	−0.60	4.00	4.80	0.80	2.93	3.79	0.86	3.80	3.91	0.11
Reading about control principles	2.67	3.36	0.70	2.80	2.60	−0.20	3.40	4.60	1.20	2.57	3.75	1.18	3.57	3.36	−0.20
Searching for and reading additional material	2.13	2.90	0.78	2.00	1.60	−0.40	2.60	4.40	1.80	2.14	2.86	0.71	2.92	3.00	0.08
Applying ways to identify control problems	2.56	3.27	0.72	2.60	2.40	−0.20	3.20	4.80	1.60	2.64	3.29	0.64	3.24	3.50	0.26
Applying procedures to solve control problems	2.63	3.10	0.48	2.40	2.60	0.20	3.40	5.00	1.60	2.71	3.50	0.79	3.32	3.59	0.27
Learning new ways to identify control problems	2.89	3.36	0.47	2.40	2.60	0.20	3.25	5.00	1.75	2.79	3.29	0.50	3.72	3.55	−0.17
Learning new procedures to solve control problems	2.88	3.20	0.33	2.80	2.40	−0.40	3.50	5.00	1.50	2.86	3.36	0.50	3.76	3.77	0.01
Solving problems to test ideas about control principles	2.44	3.09	0.65	2.80	2.20	−0.60	3.25	5.00	1.75	2.79	3.64	0.86	3.72	3.90	0.18
Taking another course or lab in controls	2.13	2.70	0.58	2.00	2.00	0.00	3.25	4.80	1.55	2.57	3.64	1.07	3.00	3.36	0.36
Conducting research on controls	2.71	3.60	0.89	2.00	2.60	0.60	3.00	4.20	1.20	2.50	3.64	1.14	3.36	3.36	0.00

class of ME Controls students and one section of the Fall 2000 class of UNIV 1301 (freshman) students, as well as for the public during UTEP's Engineering Open House in March 2001.

During the Spring 2001 semester, the lab was used by both EE and ME Controls students (in separate classes) for conducting the complete set of experiments, which was the laboratory's maiden run. Subsequently, it has been used by ME students each and every semester, and by EE students during Spring 2002. However, only the Spring 2001 and Spring 2002 EE labs, and the Fall 2002 ME lab were under the instruction of the first author, while an ME professor who has since left UTEP taught the other ME labs.

A website [13] to provide information about the laboratory to both students and the public, with pictures and descriptions of the different laboratory equipment, documentation for the various experiments and QuickTime movies of selected control experiments, has also been completed. In addition, student evaluations of this new/revised lab course were performed each time it was offered.

EVALUATION

Evaluating the degree of success of this project relied mainly on the students' self-assessment of the lab experiences' effect on their level of interest, and knowledge and skills (learning) in the controls area. A pre-test/post-test approach in the form of surveys was selected for this evaluation exercise. Hence, these assessments by the ME and EE Mechatronics Laboratory courses' students were performed at the beginning and at the end of the Spring 2001 to Fall 2002 semesters. Statistics were compiled and compared (pre to post) for those semesters that the students utilized the new laboratory and the first author was the laboratory instructor. The statistics were also compared to the baseline data on student interest and learning collected in Spring 2000 as a preliminary survey of both EE (lecture only) and ME (lecture and previous laboratory experience) Controls students. For brevity's sake, only the most significant results are presented here.

The baseline data on students' self-assessment of *interest* collected during Spring 2000 (summarized in Table 2) indicate little difference in student interest in the Controls course and related activities between beginning-of-semester levels and end-of-semester levels (means were obtained based on a 1–5 scale): the levels were slightly more positive for EE students and slightly more negative for ME students at the end of the semester than at the beginning of the semester.

Based on the stated objectives of the new lab course design, it was hypothesized that differences in levels of interest in subsequent students experiencing the new lab course would be greater than

Table 3. Two-sample comparison test showing statistical results for the mean pre- and post-test scores of all groups

	Count	Average	Variance	Standard deviation	Minimum	Maximum	Range	Standardized skewness	Standardized kurtosis
Pre_score	55	2.93455	0.266959	0.51668	2.0	4.0	2.0	0.465506	0.911929
Post_score	55	3.49182	0.67916	0.824111	1.6	5.0	3.4	0.439861	0.422646

the differences found in the Spring 2000 students (the control group).

Using the mean responses to the pre and post self-assessment surveys shown in Table 2 for the EE and ME student groups during the Spring 2000 (EE and ME control group), Spring 2001 (EE students), Spring 2002 (EE students), and Fall 2002 (ME students) semesters, statistical analyses were performed to determine:

- if there was a statistically significant difference between the mean pre and post scores for all of the student groups;
- if there was a significant difference in mean post versus pre score changes between the control group and the other groups;
- if there was a significant difference in mean pre and post scores between the EE and ME student groups.

To determine if there was a statistically significant difference between mean pre and post scores for all student groups, several tests were performed, beginning with a two-sample comparison test. This procedure calculates various statistics and graphs for each sample, and runs several tests to determine whether there are statistically significant differences between the two samples. Results of summary statistics for the two samples of data are shown in Table 3. The standardized skewness and kurtosis values lie between -2 and $+2$, indicating that these samples may come from normal distributions (values of these statistics outside the range of -2 to $+2$ indicate significant departures from normality). Therefore, a means test was appropriate. However, since the conditions for means comparisons were not present in the next two tests (either by the skewness and kurtosis being outside the range of the normal distribution or the variances not being equal as determined through the F-test), the medians were tested in order to be consistent throughout.

Consequently, a Mann-Whitney (Wilcoxon) W-test was run to compare the *medians* of the two samples (median of sample 1 is 2.86, and median of sample 2 is 3.4) by combining the two samples, sorting the data from smallest to largest, and comparing the average ranks of the two samples in the combined data. Since the P-value is less than 0.05 for this test (P-value = 0.000120342, W = 2156.0), there is a statistically significant difference between the medians at the 95% confidence level, as illustrated by the Box-and Whisker plot shown in Fig. 3.

A Kolmogorov-Smirnov test was then used to compare the *distributions* of the two samples. Computing the maximum distance between the cumulative distributions of the two samples, which in this case is 0.418182, performs this test. Since the P-value for this test is less than 0.05 (approximate P-value = 0.000133017, two-sided large sample K-S statistic = 2.19296, and estimated overall statistic DN = 0.418182), there is a statistically significant difference between the two distributions at the 95% confidence level. Based on the above, we conclude that there was a statistically significant difference at the 95% confidence level between the pre and post scores for all student groups.

The same statistical analyses described above were used to investigate if there was a statistically significant difference in mean post versus pre score changes (differences) between the control group and the other groups. The two-sample comparison results for the control group and the other groups are shown in Table 4. As before, the Mann-Whitney (Wilcoxon) W-test was run for these two samples (the median of sample 1 is 0.265 and the median of sample 2 is 0.8), and the P-value from this test is less than 0.05 (P-value = 0.00186775,

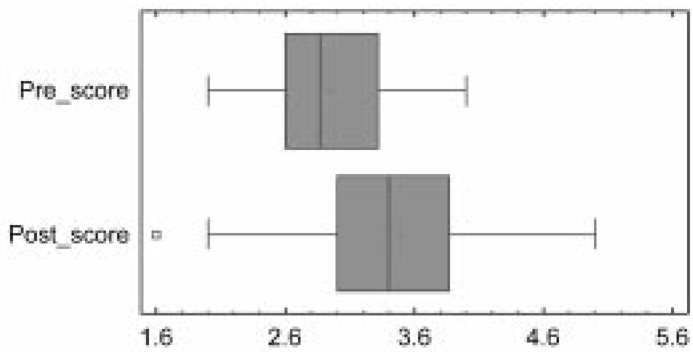

Fig. 3. Box and Whisker plot for Mann-Whitney (Wilcoxon) W-test used to compare medians of pre- and post-scores for all students.

Table 4. Two-sample comparison test showing statistical results for the mean post versus pre score changes of the control group and the other groups

	Count	Average	Variance	Standard deviation	Minimum	Maximum	Range	Standardized skewness	Standardized Kurtosis
Control_diff.	22	0.224091	0.207816	0.455868	0.6	0.89	1.49	0.914777	0.839683
Other_diff.	33	0.780909	0.379559	0.616083	0.2	1.8	2.0	0.169406	1.35628

W = 544.5), so there is a statistically significant difference between the medians at the 95% confidence level, as illustrated by the Box-and Whisker plot shown in Fig. 4. The maximum distance between the distributions using the Kolmogorov-Smirnov test was 0.5, and since the P-value is less than 0.05 for this test (approximate P value = 0.00272074, estimated overall statistic DN = 0.5, two-sided large sample K-S statistic = 1.81659), there is also a statistically significant difference between the two distributions at the 95% confidence level. Based on these tests, we conclude that there is a statistically significant difference in mean post versus pre score changes between the control group and the other groups.

Finally, statistical analyses were performed to determine if there was a significant difference in mean pre and post scores between the EE and ME student groups. In this particular case, a multiple sample comparison was required (for the different EE and ME groups shown in Table 2). As with the two sample comparison tests, various statistical tests and graphs were constructed to compare the samples, and the results are shown in Table 5. The Kruskal-Wallis test (result shown in Table 6) was used to compare the medians of the groups, and since the P-value is less than 0.05 for this test, there is a statistically significant difference amongst the medians at the 95% confidence level. The Box-and Whisker plot shown in Fig. 5 indicates that there is a significant difference between EE pre and post survey scores, but not for ME students, although the post-score median for ME is higher than the pre-score median. This result is interesting in that the ME students have traditionally taken a Controls laboratory, and did so during the Spring 2000 semester as the ME control group, while EE students have not traditionally had a laboratory experience as part of their Controls education. This result highlights not only that the new laboratory experience increased student interest in Controls as measured through student self-assessment, but also suggests that laboratory experiences in general increase student interest in the curriculum.

The analyses above provide important indications regarding the usefulness of this lab for enhancing student interest in the Controls subject. A similar analysis regarding the students' self-assessment of *learning* (knowledge and skills) in the Controls area was also performed. The results, which are detailed in [13], indicate that this lab has also slightly improved student learning of the Controls subject, by their own assessment.

COLLATERAL BENEFITS

Other courses benefiting from the development of this new laboratory are:

- UNIV 1301—Seminar/Critical Inquiry: This is a required course that serves to introduce freshman students to the various scholarly disciplines, including engineering. Demonstrations of control experiments, e.g., balancing an inverted pendulum, aim to stimulate the students' interests in the study of engineering as a means of understanding and solving real-world technical problems. It also represents an opportunity to introduce the students to the idea that present-day engineers need to be more multidisciplinary in their thinking.
- EE 4220 and EE 4230—Senior Project I and II and MECH 4466—Senior Design: A major goal of these courses is to develop a vehicle for the realization of the complete integrated process of system conception, design, fabrication, and

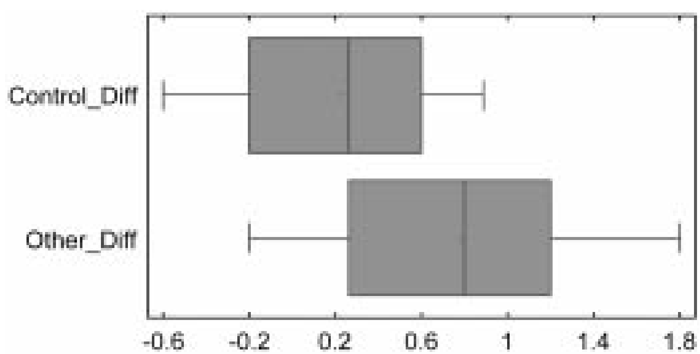

Fig. 4. Box and Whisker plot for Mann-Whitney (Wilcoxon) W-test used to compare median post versus pre score changes of the control group and the other groups.

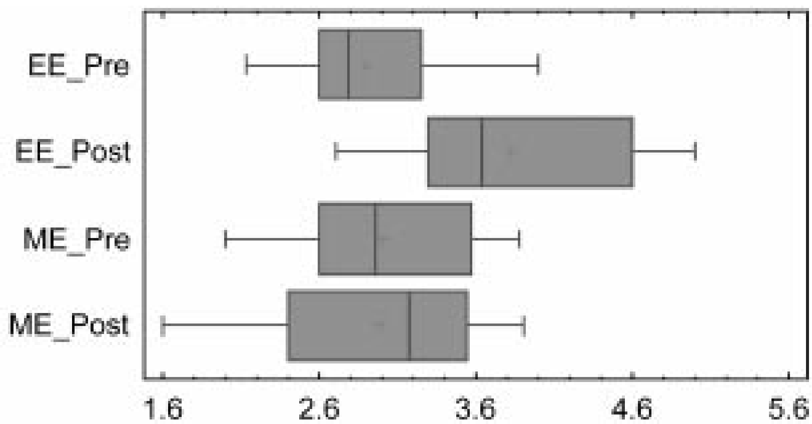

Fig. 5. Box and Whisker plot for Mann-Whitney (Wilcoxon) W-test used to compare medians of the pre- and post-scores for the EE groups and the ME groups.

Table 5. Multiple sample comparison test showing statistical results for the mean pre- and post-test scores of the EE groups and the ME groups

	Count	Average	Variance	Standard deviation	Minimum	Maximum	Range	Standardized skewness	Standardized Kurtosis
EE_Pre	33	2.88818	0.203409	0.451009	2.13	4.0	1.87	1.14819	0.122512
EE_Post	33	3.82818	0.543478	0.737209	2.7	5.0	2.3	1.01179	−1.40924
ME_Pre	22	3.00409	0.368063	0.606682	2.0	3.88	1.88	−0.430314	−0.94736
ME_Post	22	2.98727	0.473773	0.688312	1.6	3.91	2.31	−0.579745	−1.05781
Total	110	3.21318	0.54707	0.739642	1.6	5.0	3.4	2.36726	0.422821

Table 6. Kruskall-Wallis test (test statistic = 27.8087, P-value = 0.00000398385) used to compare medians of the pre- and post-scores for the EE groups and the ME groups

	Sample Size	Average Rank
EE_Pre	33	40.7576
EE_Post	33	79.4848
ME_Pre	22	48.3636
ME_Post	22	48.7727

verification. Controls-related projects are organized such that the student groups are faced with the conceptualization, design, fabrication, and implementation of a system, e.g., a motorized wheelchair to satisfy given requirements.

CONCLUSIONS

A state-of-the-art Mechatronics laboratory, for use by both Electrical Engineering and Mechanical Engineering students, was recently developed at UTEP. From the evaluation results described above, based on quantitative analyses of student self-assessments collected over a period of two years, we conclude that the establishment of this laboratory has helped to increase students' level of interest in the Controls subject. An accompanying evaluation also indicates that this new lab course has slightly improved student learning. These conclusions also suggest, by inference, that similar labs at other institutions should be achieving the same positive effects on student interest in and learning of the Controls subject. Moreover, the documentation here of quantitative evaluation results regarding the effectiveness of this Mechatronics lab in meeting its design objectives should serve as a benchmark for more effective future design of such labs.

For the foreseeable future, the laboratory's website will be regularly updated and kept accessible to the public. In addition, we will continue to conduct demonstrations of the laboratory's capabilities during Engineering Open House and student recruitment visits to campus, as well as to show videotapes of our undergraduates performing the control experiments during off-campus student recruiting visits to stimulate their interest in the study of engineering. These actions will thereby extend the impact of this lab beyond the confines of the UTEP campus for promoting interest in the study of controls and mechatronics.

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REFERENCES

1. E. Dale, *Audio-Visual Methods in Teaching*, Holt, Rinehart and Winston, New York, NY (1997).
2. *The Vision for Change, A Summary Report of the ABET/NSF/Industry Workshops*, Accreditation Board for Engineering & Technology, Baltimore, MD (1995).
3. S. H. Johnson, W. L. Luyben and D. L. Talhelm, Undergraduate interdisciplinary controls laboratory, *J. Eng. Educ.*, 1995, pp. 133–136.
4. B. J. Furman *et al.*, Laboratory development for mechatronics education, *Proc. ASEE National Conference*, Washington, DC, June 1996.
5. R. C. Arkin, K.-M. Lee, L. F. McGinnis and C. Zhou, The development of a shared interdisciplinary intelligent mechatronics laboratory, *J. Eng. Educ.*, 1997, pp. 113–118.
6. H. Wong, V. Kapila, and A. Tzes, Mechatronics/Process Control Remote Laboratory, *Proc. ASEE National Conf.*, Albuquerque, NM, June 2001.
7. B. Diong, Providing an Updated Control Systems Lab Experience, *Proc. ASEE National Conf.*, Charlotte, NC, June 1999.
8. URL: http://www.ehr.nsf.gov/EHR/DUE/programs/ccli/; NSF Course, Curriculum, and Laboratory Improvement (CCLI) program.
9. URL: http://www.mathworks.com/; The MathWorks: Developers of MATLAB and Simulink for Technical Computing.
10. URL: http://www.dspaceinc.com/; dSPACE—Solutions for Control.
11. URL: http://www.dspt.com/; DSP Technology.
12. URL: http://www.ecpsystems.com/; Educational Control Products.
13. URL: http://www.ece.utep.edu/~webbdiong/dsclab/index.html; The University of Texas at El Paso College of Engineering's Mechatronics Lab.

APPENDIX

UTEP controls courses

- **EE 4364—Systems and Control:** This is the elective introductory controls course for senior-level electrical engineering students. Prerequisite: Signals and Systems. Present textbook: Kuo.It emphasizes the following:
  - Modeling, analysis and design of continuous time linear dynamic systems;
  - Relationships between frequency and time domain modeling, analysis and design;
  - Analysis of system stability and performance using various techniques;
  - Design of PID, lead-lag and state-feedback controllers.
- **MECH 4311—Automatic Controls:** This is the required introductory controls course for senior-level mechanical engineering students. Prerequisite: Dynamic Response. Present textbook: Ogata. It emphasizes the following:
  - A study of classical control theory including transfer functions, stability and time response, error analysis and sensitivity functions, root locus, Nyquist diagrams, and Bode plots;
  - An introduction to modern control theory.
- **MECH 4111—Controls Laboratory:** This is a required course for senior-level mechanical engineering students. Concurrent requisite or pre-requisite: Automatic Controls. It previously emphasized the following:
  - Experiments on spring-mass-damped systems, internal structural damping, forced vibrations, open and closed loop pneumatic systems, servomotor control, and control simulator.

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