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Student motivation and academic success: Examining the influences, differences, and economics of mechatronic experiences in fundamental undergraduate courses

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Student motivation and academic success: Examining the influences, differences, and economics of mechatronic experiences in fundamental undergraduate courses

by

John R. Haughery

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Industrial and Agricultural Technology

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Iowa State University

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DEFINITION OF TERMS

Academic Success: A combination of *academic achievement* (e.g., grades and GPA), *attainment of learning outcomes* (e.g., student engagement and proficiency profile), and *acquisition of skills and competencies* (e.g., critical thinking and problem solving) (York, Gibson, & Rankin, 2015).

Accreditation: The process by which an academic degree program is certified by a third-party accreditation body (e.g., ABET, ATMAE, etc.).

Cost-Effectiveness Analysis: The incremental cost ($) per unit of incremental effect. This enables an incremental cost per incremental unit effect ratio (CER) or incremental effect per incremental unit cost ratio (ECR) to be calculated (McEwan, 2012).

Cost Ingredients: Cost categories of an intervention or experience that can be quantified and compared against incremental effects. Ingredients included: *personnel* (i.e., full-time, part-time, consultant, volunteer, etc. human resources) and *equipment and materials* (i.e., furniture, scientific apparatus, instructional equipment, experience material, computer equipment, commercial tests, etc.) (Levin & Belfield, 2015).

Engineering/Technology Education: The educational fields specifically related to the academic education of engineers and/or technologists at the collegiate level. No distinction was made between the fields of engineering and technology, as they are very closely related when considering the focus of this research.

Fundamental Course: A course that contains some of the core curricular requirements of a degree program and is taking during the freshman year of undergraduate education.

Incremental Cost Analysis: Costs incurred by an intervention or experience that are above and beyond the *status quo*, as defined by Levin and McEwan's (2001) costs "ingredient" approach. These costs function as opportunity costs and offer a direct mechanism for quantifying the economics of an experience (Levin & Belfield, 2015).

Learning Retention: The components of *academic achievement*, *attainment of learning outcomes*, and/or *acquisition of skills and competencies,* and the degree to which students can retain and show mastery of these components.

Mechatronics: The "synergistic combination of precision mechanical engineering, electronic control and systems thinking in the design of products and manufacturing processes" (Grimheden & Hanson, 2005, p. 180).

Mechatronic Experience: A project, laboratory, or contest using mechatronic platforms that required students to combined mechanical, electrical, and computer systems to complete an application task.

Motivational Orientation: An individual's motivational focus or effort, as determined by their levels of *value choices* and *expectancy beliefs*. The constructs of Intrinsic Goal Orientation (IGO), Extrinsic Goal Orientation (EGO), and Task Value (TV) were used to measure levels of *value beliefs,* while Control of Learning Beliefs (CLB), Self-Efficacy (SE), and Test Anxiety (TA) were used to measure *expectancy choices.* All of these dimensions can be measured using the *Motivated Strategies for Learning Questionnaire* (MSLQ) (Pintrich & Others, 1991).

Student Engagement: A student's involvement, interest, or curiosity toward curricular topics such as (but not limited to): student learning outcomes, project objectives, or assignment requirements (Light, 1992, 2004). While non-

Student Motivation: A social-cognitive model of motivation that includes the dimensions of *expectancy beliefs* (i.e., *self-efficacy*, *attributions*, and *control beliefs*), *value choices* (i.e., *goal orientation*, *interest*, and *importance*), and *meta-cognition* (i.e., *self-regulated* learning) (Pintrich, Marx, & Boyle, 1993). This motivation-cognition model took the perspective that meta-cognition and motivation form a symbiotic and dynamic relationship. A person continually evaluates intrinsic and extrinsic feedback to dynamically adjust their motivation towards learning (Schunk & Zimmerman, 2012). When this happens, a student is said to be self-regulating their learning (termed *self-regulated learning*), with the cognitive "energy" expended being labeled as *motivation* (Schunk & Zimmerman, 2012, p. 306).

ACKNOWLEDGMENTS

Among the many individuals who have helped and supported my research, a few are significant. First, my wife Cori, my son Porter, and my daughter Mariya for their tireless love and care. Next, my major professor Dr. D. Raj Raman for his unwavering support and guidance. My committee members Dr. Steven A. Freeman, Dr. Amy L. Kaleita, Dr. Joanne K. Olsen, and Dr. Robert A. Martin for their meaningful engagement and input, as well as MaryAnn Grapp for her superb purchasing coordination. And finally, the Department of Agricultural and Biosystems Engineering at Iowa State University for allowing me to test my ideas in the classroom, and funding my efforts from its graduate Teaching and Research Assistantship. Without the support from these people and my department, my research would not have been completed. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

ABSTRACT

In this study, we examined influences, differences, meanings, and economics of mechatronic experiences in a first-year, fundamental technology course. Our first objective examined the primary and secondary influences of mechatronic experiences on student engagement. Using a systematic review methodology, we collected n=402 articles. Screened by title and abstract, we mapped six parent and 22 child codes to the remaining n=137 articles. From these, we appraised n=17 studies, assessed eight as high quality, from which we identified five primary influences (*Student Motivation, Self-Efficacy, Course Rigor, Learning Retention,* and *Gender*) and two secondary influences (*Accreditation* and *Ease-of-Implementation*). In these influences, we found evidence that mechatronic experiences can increase student motivation, self-efficacy, and course rigor. Also, positive impacts on learning, gender diversity, accreditation efforts, and ease of course content implementation were identified.

Our second objective was to quantify differences in students' motivational orientation and academic success in a mechatronic experience vs. a non-mechatronic experience. To this end, we developed, piloted, and deployed a mechatronic experience in a first-year technology course. Using a quasi-experimental, non-equivalent control vs. treatment design (n=84) we found no statistically significant difference in students' motivational orientation – specifically *value choices* [$F(6,77)=0.13$, $p=0.7224$] and *expectancy beliefs* [$F(6,77)=0.38$, $p=0.5408$] – between mechatronic and non-mechatronic experiences. This is an encouraging outcome, as literature would indicate students' motivation drops over the course of a semester and wane towards the end of a

project. In contrast, statistically significant increases in project scores [$F(5,78)=6.51$, $p=0.0127$, $d=0.48$, $d_{95\%CI}=0.00$ to 0.98] and course grades [$F(5,78)=7.76$, $p=0.0067$, $d=0.70$, $d_{95\%CI}=0.20$ to 1.20] were observed in the mechatronic experience group (three and eight percentage points, respectively). However, when we analyzed the correlation between motivational orientation and academic success, we found no relationship. We concluded that students' motivational orientation did not moderate differences in academic success, as others have indicated.

Our final objective was to quantify the costs and scalability of implementing our mechatronic experience. We found limited literature focusing on costs of such efforts, and therefore developed a novel costing method adapted from medical and early childhood education literature. We implemented this method using marginal (above baseline) time and cost ingredients that were collected during the *development*, *pilot*, and *steady-state* phases of the mechatronic experience. Our evaluation methods included descriptive statistics, Pareto analysis, and cost per capacity estimate analysis. For our 121-student effort, we found that the *development, pilot,* and *steady-state* phases cost just over \$17.1k (~\$12.4k for personnel and ~\$4.7k for equipment), based on 2015 US\$ and an enrollment capacity of 121 students. Total cost vs. capacity scaled at a factor of -0.64 ($y = 3{,}121x^{-0.64}$, $R^2 = 0.99$), which was within the 95% interval for personnel and capital observed in the chemical processing industry. Based on a four-year operational life and a range of 20 – 400 students per year, we estimated per seat total costs to range from \$70 – \$470, with our mechatronic experience averaging just under \$150 per seat. Finally, the *development* phase cost, as well as the robot chassis and microcontroller capital cost were the primary cost terms for our mechatronic experience.

CHAPTER 1. OVERVIEW OF RESEARCH

Introduction

According to Meece, “The goal of any educational program must be to create a learning environment that supports or elicits students’ intrinsic interest in learning.” (1997, p. 34) Many would argue that learning equates to academic success. However, according to a systematic review by York, Gibson, and Rankin (2015), academic success is defined in the literature by six primary facets: academic achievement, satisfaction, attainment of learning, persistence, career success, and the acquisition of skills and competencies. Wilson *et al.* (2014) postulated that student engagement is an intermediate outcome to academic success, and is evident in students within a shorter timeframe than the other facets (e.g.., *academic achievement*, *persistence*, etc.). Nelson *et al.* (2015), consider student engagement as directly proportional to learning achievement. von Strumm, Hell, and Chamorro-Premuzic (2011) found the interaction effects between student effort and student intellectual engagement (i.e., intellectual curiosity) to be a good predictor of academic success. Similarly, Light (1992, 2004) denoted student engagement (i.e., student involvement in learning) as a critical factor in educational development, while Kamphorst, Hofman, Jansen, and Terlouw (2015) indicated it as pivotal to student persistence. Pintrich, Smith, García, and McKeachie (1993) suggest engagement to be a function of student motivation. They indicate that students’ motivational beliefs affect cognitive engagement. Many more suggest that self-efficacy (a construct of motivation) is a strong predictor of performance, persistence, and engagement (Halbesleben, 2010; Simbula, Guglielmi, & Schaufeli, 2011; Vera, Le Blanc, Taris, & Salanova, 2014;

Xanthopoulou, Bakker, Demerouti, & Schaufeli, 2007). Meece (1997, p. 77) states that, "…the heartbeat of the student…" is their motivation towards learning. In all this, it is evident that a strong link exists between the high-level outcome of academic success and the low-level construct of student motivation. More importantly, it appears that the over-arching outcome of academic success can be positively influenced by how students are motivated to engage in learning.

Linnebrinck-Garcia (2011) show that classroom activities influence student motivation. Meece (1997, p. 3) states that, "…schools and teachers can encourage or discourage…learning through the ways in which they structure the learning environment." Furthermore, student motivation is "sensitive to context" and, "…schools can make changes in the learning environment that increase the number of students who stay engaged and motivated…" (1993). Pintrich *et al*. (1993), further support this notion, indicating that real-world projects and activities in the classroom can help motivate students to engage with learning. Many have pointed to mechatronic experiences (i.e., those combining mechanical, electrical, and computer systems) as real-world, hands-on projects that can positively affect undergraduate engineering and technology students' motivation to learn (Bolanakis, Glavas, & Evangelakis, 2007; Castles, Zephirin, Lohani, & Kachroo, 2010; McLurkin, Rykowski, John, Kaseman, & Lynch, 2013; Nedic, Nafalski, & Machotka, 2010; Verner & Ahlgren, 2004). Not surprisingly, mechatronic experiences have been implemented in a variety of science, technology, engineering, and mathematics (STEM) curricula, particularly undergraduate courses in the electrical, mechanical, and computer fields. These experiences have ranged from stand-alone modules to complete course implementations culminating in applied projects.

Purpose

The literature strongly suggests that mechatronic experiences can influence student engagement and academic success. However, many questions of relevance to practitioners remain unanswered, including: What are the most common areas in which mechatronic experiences influence student engagement? How much of a difference in academic success is observed when students engage in a mechatronic experience? Why do these experiences have a positive impact? What are the distinct aspects at work in this phenomenon? What is the economic impact of these experiences (i.e., do the benefits outweigh the costs)? When examining past and current literature surrounding mechatronic experiences in undergraduate courses, we found limited empirical evidence with which to answer these questions. Therefore, we sought to accomplish three objectives. Embedded within each of these objectives were corresponding research questions that guided our methods, analysis, and framed our conclusions. The relationship between these objectives is graphically depicted in Figure 1.1.

Objective 1

Systematically review current literature to identify primary and secondary influences of mechatronic experiences on student engagement. To achieve this, we asked the following research question:

- What are the primary and secondary influences of mechatronic experiences on student engagement in fundamental engineering courses?

Objective 2

Quantify the differences in student motivation and academic success in a mechatronic experience vs. a non-mechatronic experience. The following research questions was asked:

- Did students in the treatment group have different levels of motivational orientation and academic success compared to those in the control group?
- Was there a difference in the proportion of students who reported being motivated in the treatment group compared to the control group?
- What was the relationship between students' motivational orientation and academic success, and did it differ in the treatment group vs. the control group?

Objective 3

Quantify the costs and scalability of a mechatronic experience. We asked the following research questions:

- What incremental costs are associated with implementing a mechatronic experience?
- How do these costs scale with class size?

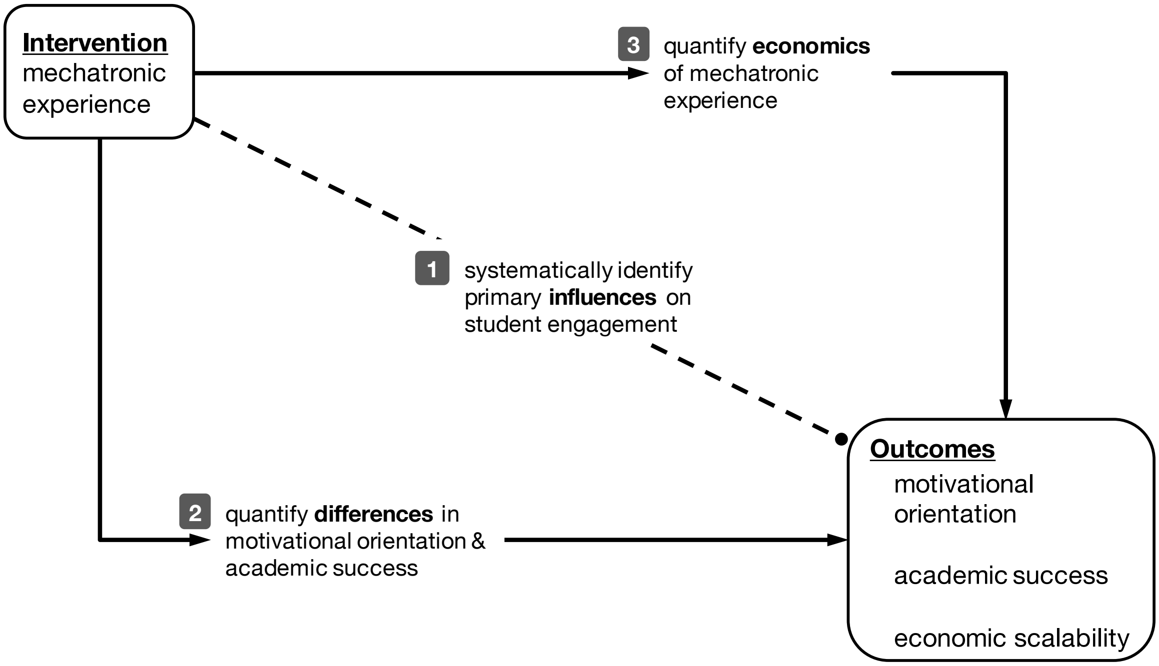

Figure 1.1
Illustration of the relationship between the study's intervention, research objectives (numbered items), and outcomes.

Rationale

Why study the influences, differences, meanings, and economics of mechatronic experiences relative to student motivation and academic success? Because it has the potential to provide authentic benefit to both students and educators. Many researchers indicate student motivation to be directly associated with student engagement (Gellin, 2003; Pike, 1999, 2000; Pike & Killian, 2001). Student engagement has also been found to be a strong predictor of academic success (Kamphorst et al., 2015; Light, 1992, 2004; Nelson et al., 2015; von Stumm et al., 2011; Wilson et al., 2014). Moreover, Nelson *et al.* (2015) found almost 83% of engineering students in a fundamental computer science course to exhibit maladaptive motivation profiles (e.g., apathetic, surface learning, learned helplessness). This maladaptation led to lower course grades and has been found by Shell and Soh (2013) to decrease students' motivation. Many indicate that mechatronic experiences are a tangible in-class experience that can positively motivate students towards engaging with course content (Bolanakis et al., 2007; Castles et al., 2010; Durfee, 2003; McLurkin et al., 2013; Nedic et al., 2010; Troni & Abusleme, 2013; Verner & Ahlgren, 2004). Therefore, better understanding how mechatronic experiences impact student motivation and academic success can help educators make research-based decisions in the classroom, as well as provide practical benefits to students as they pursue their academic goals.

There is potential benefit to educators and funding agencies in understanding the costs and scalability of mechatronic experiences. While some research has been conducted on this topic (McLurkin et al., 2013; Shamlian, Killfoile, Kellogg, & Duvallet, 2006; Troni & Abusleme, 2013), it has focused primarily on equipment costs while leaving out other critical costs of implementing mechatronic experiences. This is especially relevant in light of a 30% decrease in state funding of higher education between 2000 and 2014 (American Academy of Arts & Sciences, 2015). Empirically quantifying the costs and scalability of mechatronic experiences may enable educators and funding agencies to make more informed curricular and budgetary decisions.

Methodology

At a high level, we employed a mixed method approach. We triangulated quantitative and qualitative data (Creswell & Plano Clark, 2007) to strengthen the internal validity of our study (Denzin, 1978). This was intended to improve the accuracy and generalizability of our interpretations (Leedy & Ormrod, 2013). We describe the methods used to achieve each objective, within the corresponding chapters that dealt with that objective.

Structure

This dissertation followed the manuscript format. Chapter 1 introduced the research, detailed the purpose of the study (i.e., research objectives), resented a rationale for why the research was beneficial, and gave a broad overview of the methods used to accomplish each objective.

Chapter 2, published in the *International Journal of Engineering Education,* systematically reviewed the literature surrounding primary and secondary influences of mechatronic experiences on student engagement. The results of this paper were a synthesis of the influences of mechatronic experiences, and informed the scope of the objectives in Chapter 3 and Chapter 4. Specifically, Chapter 2 found student motivation as a primary influence of mechatronic experiences in first-year fundamental engineering/technology courses. The first author, John R. Haughery, was the primary researcher, corresponding author, and a graduate student in the Department of Agriculture and Biosystems Engineering at Iowa State University at the time of publication. The second author, D Raj Raman, was the major professor and provided intellectual guidance during the preparation of the manuscript.

The second objective was covered in Chapter 3, and will be submitted for publication to the journal of *Learning and Instruction*. This chapter quantified differences in student motivation and academic success for a mechatronic experience vs. a non-mechatronic experience. Results showed no difference in motivational orientation, while statistically significant differences were found in academic success. Moreover, no relationship between motivational orientation and academic success were found. The first author, John R. Haughery, was the primary researcher, corresponding author, and a graduate student in the Department of Agriculture and Biosystems Engineering at Iowa State University. The second author, D Raj Raman, was the major professor and provided intellectual guidance during the preparation of the manuscript. The third author, Joanne K. Olson, was a committee member and provided guidance on education and student motivation theory. The forth author, Steven A. Freeman, was a committee member and provided theoretical and structural guidance during the preparation of the manuscript. The fifth author, Amy L. Kaleita, was a committee member and provided structural input during the preparation of the manuscript. The sixth author, Robert A. Martin, was a committee member, and provided input on student learning theory.

Chapter 4 addressed our third objective of quantifying the costs and scalability of implementing a mechatronic experience. This chapter will be submitted for publication in the *Journal of Engineering Education*, as it represented a novel method for quantifying the economics of conducting an experience in engineering education. We used our mechatronic experience as an exemplary dataset to illustrate our methods, and found the most significant costs to be the instructor's time, the robotic chassis, and the microcontroller. Additionally, total cost vs. capacity exhibited scaling factors that benefit large class sizes. The first author, John R. Haughery, was the primary researcher, corresponding author, and a graduate student in the Department of Agriculture and Biosystems Engineering at Iowa State University. The second author, D Raj Raman, was the major professor and provided intellectual guidance during the preparation of the manuscript.

Chapter 5 concluded this dissertation by reviewing our research objectives and questions, results, and recommendations for future research. Appendices were also included at the end of this document. They give further details to the methods and measurement tools used in Chapters 2 – 4, but were not explicitly referenced in these manuscripts. Finally, our study's Institutional Review Board (IRB) exempt approval form was included as the last appendix.

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CHAPTER 2. INFLUENCES OF MECHATRONICS ON STUDENT ENGAGEMENT IN FUNDAMENTAL ENGINEERING COURSES: A SYSTEMATIC REVIEW

Modified from typeset manuscript published in the *International Journal of Engineering Education, Vol. 32, Issue 5, 2016*

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Abstract

In our review, we examined the primary and secondary influences of mechatronic experiences on student engagement in fundamental engineering courses. Using a systematic review methodology, we collected 402 articles with publication dates ranging from 1990 – 2014. Screening on title and abstract information reduced our included sources to 137, from which we mapped six parent and 22 child codes. Appraising 17 of these articles we identified eight high quality studies as the focus of our synthesis, which identified five primary influences (*Student Motivation, Self-Efficacy, Course Rigor, Learning Retention,* and *Gender*) and two secondary influences (*Accreditation* and *Ease-of-Implementation*). In these influences, we found evidence that mechatronic experiences can increase student motivation, self-efficacy, and course rigor. Also, positive effects on learning retention, gender diversity, accreditation efforts, and ease of course content implementation were identified. Future research is needed to clarify: 1) if mechatronic experiences truly increase student motivation and self-efficacy more than lecture-based strategies, 2) how the positive short-term impacts of these experiences translate to subjective academic success (i.e., future course and career goals), 3) how implementation logistics are influenced by experience type (i.e., open-ended projects verse contests), class size, institution and industry support, etc., and 4) to what degree the factors of gender, underrepresented student groups, course curricular placement, and activity type influence student engagement.

Keywords: student engagement; mechatronics; problem-based learning; project-based learning

Introduction

For over two decades, engineering educators have deployed hands-on problem-based learning (PbBL) and project-based learning (PjBL) pedagogies in undergraduate courses in the hopes of "produc[ing] broad-based, flexible graduates who can think integratively, solve problems and be life-long learners" (Matthew & Hughes, 1994, p. 234). These types of efforts are well aligned with Papert and Harel's (1991) concept of constructionism, in which students play an active role in learning by making or creating a tangible artifact. Many of these studies have specifically used mechatronic experiences (e.g., projects, laboratories, or contests using mechatronic platforms) to increase student engagement (e.g., interest or curiosity in academics). According to Verner and Ahlgren (2004), mechatronic-themed experiences are an especially clear example of this approach in education; the artifact in these experiences being mechanical and electrical hardware components joined and controlled by computer software, which in summation comprise a mechatronic system. Grimheden and Hanson (2005, p. 180) further define mechatronics as the "synergistic combination of precision mechanical engineering, electronic control and systems thinking in the design of products and manufacturing processes." It is perhaps not surprising that mechatronic experiences have been implemented in a variety of science, technology, engineering, and mathematical (STEM) curricula, particularly electrical, mechanical, and computer fields. Shull and Weiner (2002) conducted a study in which an increase in female students' self-efficacy (e.g., belief in one's ability to accomplish a goal or control an outcome) and student motivation (e.g., a desire to work and learn) was observed after conducting hands-on electronic hardware and software experiences. Others have analyzed a broader range of experiences specific to mechatronics. These have included stand-alone content modules to complete course implementations culminating in applied projects where students are required to exhibit a mastery of a variety of course outcomes (Verner & Ahlgren, 2004; Durfee, 2003; McLurkin et al., 2013; Castles et al., 2010; Bolanakis et al., 2007; Sarkar & Craig, 2006; Nedic et al., 2010; Troni & Abusleme, 2013). Yet, continued research is called for that will deepen the field's understand of the impact these experiences have on student engagement (Yadav, Subedi, Lundeberg, & Bunting, 2011).

Purpose

To understand the broad results of past efforts, our paper addressed the research question: "What are the primary and secondary influences of mechatronic experiences on student engagement in fundamental engineering courses?" We define *fundamental course* as pertaining to those that teach fundamental engineering topics (i.e., problem solving) and are commonly taken by freshman or sophomore students, *primary influences* as directly influencing students, and *secondary influences* as influencing those responsible for implementing the experience. Developing a framework for these influences will help to clarify connections between student engagement and mechatronics, and achieve the first objective of our broader research study.

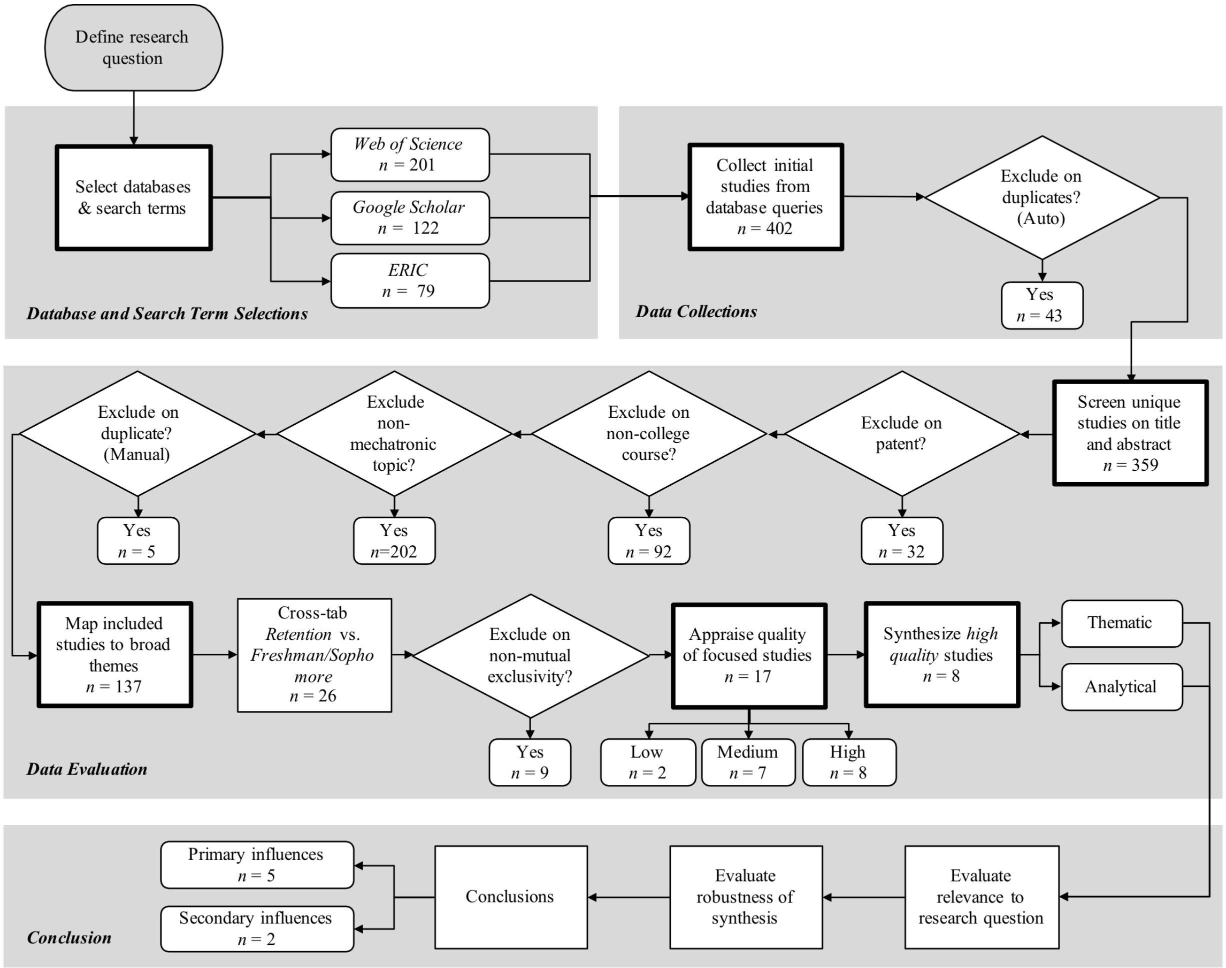

Figure 2.1
Methodology structure and data flow of systematic review (gray areas indicate demarcations between major phases, with article counts denoted by *n*).

In the following sections, we present the results of our systematic review of relevant literature. These results include explanation of our categorization strategies, a tabulation of the thematic trends and gaps in the literature, a quality appraisal of the literature, and an in-depth thematic and analytic synthesis of the literature germane to our research question. The intent is to produce original knowledge on the topic of mechatronic experiences in fundamental undergraduate courses. In so doing, we hope to enable future efforts towards increasing engagement of freshman and sophomore engineering students at the collegiate level.

Database and Search Term Selection

The first phase of our review was to select suitable databases from which to collect relevant articles (Figure 2.1). To facilitate easy integration of articles into the document management software EPPI Reviewer $4^{©}$ (Thomas, Brunton, & Graziosi, 2010), we limited searches to electronic databases. This electronic format also allowed us to efficiently analyze and control our search results, thereby giving us a systematic and traceable process of filtering, including, excluding, and rating each piece of literature. We selected Web of Science (Thomas Reuters), Google Scholar (Google), and ERIC (Institute of Education Sciences) based on a qualitative analysis of the breadth and depth of each databases' educational and technical content collections, as well as advanced query functionality.

Next, we selected the search terms in Table 2.1. Determining the exact string combinations was a multifaceted process. The first step was to select very *sensitive* strings, which returned large numbers of articles (i.e., broad in scope). Next, very *precise* strings were used, which returned relatively smaller numbers of articles (i.e., narrow in scope). In addition, we used a mixed-method strategy, which combined the broad and narrow aspects of sensitive and precise strategies into one query. An example of this was performed using Web of Science and started with a sensitive search that returned 1,423 articles. The first 100 of these were scanned and ~10% were found to be irrelevant to our research question. Based on this, our query was repeated using *Title* instead of *Topic*. In this way, the sensitivity was retained while adding precision to the search without changing the terms. The subsequent outcome of this revised search returned 131 articles. All three databases were queried using this strategy to maximize the quality and quantity of relevant articles returned, as suggested by Gough, Oliver, and Thomas (2012).

Table 2.1
Search terms and strategies used for each databases.

Database	Precise Search Terms	Sensitive Search Terms
Web of Science	TOPIC: (mechatronic* or microcontrol* or micro control*) AND TOPIC: (problem or project based) AND TOPIC: (engineer* or technol*) AND TOPIC: (course or class or curricula*) NOT TOPIC: (medicine* or health* or surgery* or design or simulation)	TITLE: (mechatronic* or microcontrol* or micro control*) AND TITLE: (course or class)
Google Scholar	(*Precise* terms not used due to unreliable results.)	TITLE: (mechatronic AND microcontroller AND course AND class)
ERIC	TOPIC: (mechatronic* or microcontrol* or micro control*) AND TOPIC: (problem based learning) AND TOPIC: (engineer* or technol*) AND TOPIC: (course or class or curricula*)	TOPIC: (robot* or microcontrol* or micro control*) AND problem based learning

We did not include the search term “robot” or any of its variants, because it was overly sensitive, even when used within *Title* searches (e.g., removing this term alone reduced one search from 534 to 131). Furthermore, we observed that most of the query results using this term were related to advanced robotic research or medical robotic research, both of which were not within the scope of our review.

Next, we chose the publication date range of 1990 – 2014 based on an analysis of the publication dates within one of our initial search results. First, the frequency distribution of publications per year in Figure 2.2 was generated using a sensitive search strategy within Web of Science in conjunction with the sites Citation Report tool. Based on these results, all articles published prior to 1990 (light gray) were screened on title and found to be either a United States Patent filing or a medical related article. In short, none were relevant to mechatronic experiences in fundamental undergraduate engineering courses and were therefore not considered relevant to our review.

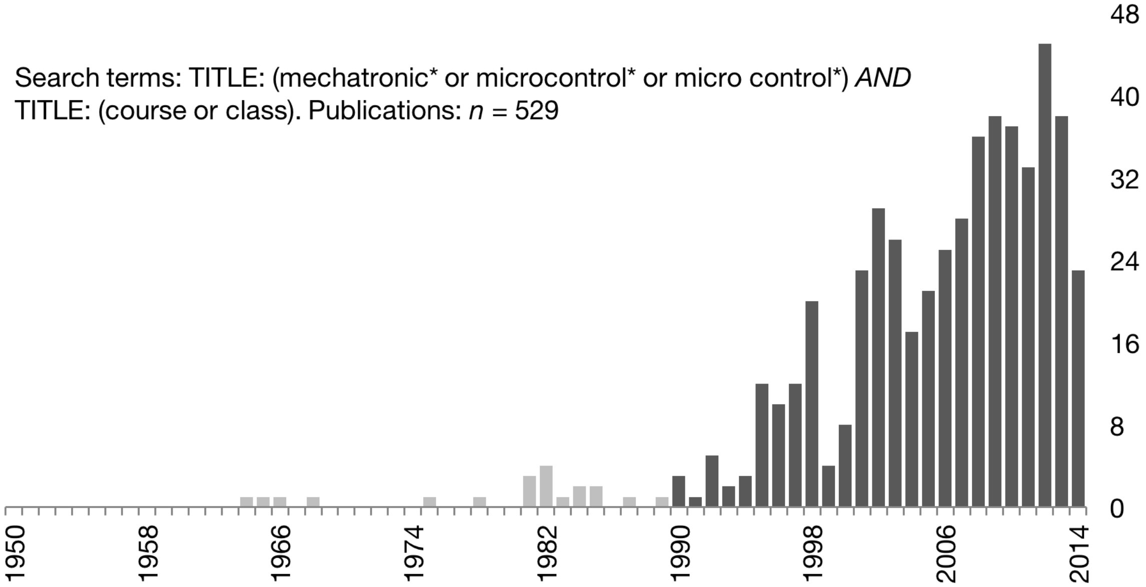

Figure 2.2
Preliminary search results for publication date frequencies. (*Source*: Web of Science).

Data Collection

On September 9th, 2014, we collected a total of 402 articles from Web of Science, Google Scholar, and ERIC. Bibliographic information for each was uploaded to EPPI Reviewer 4©, at which point 43 duplicates were identified and removed using an automatic software algorithm that looked at title and abstract keywords. This process reduced the total article count to 359, which were passed to the data evaluation phase (Figure 2.1).

Data Evaluation

We employed a four-stage data evaluation process that included screening, mapping, appraising, and synthesizing each included article. We conducted each of these at strategic points in the review with the intent of reaching a distilled list of sources relevant to answering our research question. The findings from these stages are described below and illustrated in Figure 2.1.

Results

Screening

At the outset of our screening process, 359 sources were vetted based on title and abstract information. The result of this screening reduced our data set to 137 articles (~62% reduction). The exclusion codes used in this stage are listed as diamonds in Figure 2.1, with corresponding counts of excluded articles. If an article qualified for one or more of the exclusion codes, it was excluded. If no exclusion code was given, by default an include code was applied and it was carried forward to the subsequent mapping stage. It is important to note that these codes (and those used throughout our review) were not mutually exclusive, as multiple articles could be given the same code(s) and *vice versa*. Even so, by coding the studies in this way, non-pertinent articles were filtered out, leaving only those applicable to our research question.

Mapping

The purpose of the mapping phase was to allow us "to describe the nature of [the] field of [our] research", "to inform the conduct of [our] synthesis", and "to interpret the findings of [our] synthesis" relative to mechatronic projects in fundamental engineering courses (Gough et al., 2012, p. 46). To that end, we conducted a thorough review of title and abstract information of each of the remaining 137 articles. As themes were identified in the literature, broad parent-codes and narrow child-codes were assigned to each article (Table 2.2). These codes were selected based on the combination of 1) commonly observed terms in the literature, and 2) to translate and consolidate terminology across the literature. These codes functioned as tags, identifying which themes were manifested by which sources of literature.

From this mapping process, we could gain insights into recurring themes and methods across all included studies (Table 2.2). The parent-codes identified included *Course Level, Content Delivery Method, Pedagogy, Investment Level/Duration, Improvement Process,* and *Academic Success*. Corresponding to each of these were multiple child-codes (Table 2.2), which represent more precise sub-divisions within each parent-code.

This mapping enabled us to identify a set of salient themes from which to build a configurative review of the literature to answer our research question (Dixon-Woods et al., 2006). From Table 2.2 Experiential *Learning (PjBL/PbBL)* and *Course* were both mapped to the largest percentage of the 137 studies, at 50% and 47% respectively. These high percentages are not surprising, as the search strategy we employed specifically included the terms “problem or project based” and “course or class.” Further examination of our mapping results reveals the child-codes of *Reflections on Methods*, *Freshman/Sophomore*, *Junior/Senior*, *Student Engagement*, and *Program (Curricula)* were each applied to roughly 20% to 30% of the articles. The remaining 17 child-codes applied to the fewest percentage of studies, each with values below 15%.

From our mapping results, we cross-tabulated articles with the parent-codes of *Academic Success* and *Course Level* (Table 2.3). From these, we specifically analyzed those exhibiting *Academic Success* and the child-code of *Freshman/Sophomore*. This resulted in 26 articles, of which 17 were mutually exclusive. We selected these unique articles for our quality appraisal because they focused on student engagement in fundamental undergraduate engineering courses.

Table 2.2
Results of mapping parent- and corresponding child-code to 137 salient studies.

Parent-code [a]	Child-code [a]	Count	(%)
Course Level	Graduate	19	*(14)*
	Junior/Senior	26	*(19)*
	Freshman/Sophomore [b]	28	*(20)*
Content Delivery Method	Module	12	*(9)*
	Remote (Online)	12	*(9)*
	Lab	17	*(12)*
	Program (Curricula)	26	*(19)*
	Course	64	*(47)*
Pedagogy	Active Learning (Group-Based)	11	*(8)*
	Reflections on Methods	31	*(23)*
	Experiential Learning (PjBL/PbBL)	68	*(50)*
Investment Level/Duration	Preparation Time	2	*(1)*
	Support: Institution	2	*(1)*
	Material Cost	8	*(6)*
	Support: Industry	12	*(9)*
Improvement Processes	Continuous Improvement	2	*(1)*
Academic Success	Gender Related [b]	1	*(1)*
	Persistence [b]	2	*(1)*
	Freshman [b]	4	*(3)*
	Self-efficacy [b]	4	*(3)*
	Performance (Follow-forward) [b]	14	*(10)*
	Student Engagement [b]	28	*(20)*

[a] Codes not mutually exclusive. [b] Codes identified as the focus of future research.

Quality Appraisal

According to Gough, Oliver, and Thomas (2012), a vital phase of systematic reviews is a quality appraisal of the literature. Therefore, we evaluated the full-text of each of the 17 sources of literature identified from Table 2.3. From this analysis, we calculated a *Composite Quality Score* (Q_{CS}) for each article, which served as a Weight of Evidence (WoE) value. These scores were used to identify studies of highest quality and relevance to our research question. The WoE framework used was borrowed from the work of others and included the evaluation dimensions of *soundness of study* (Dixon-Woods et al., 2006), *appropriateness of study,* and *relevance of study* (Gough et al., 2012). Using this framework allowed us to appraise the quality of our relevant sources more objectively (not withstanding some inherent subjectivity).

Table 2.3
Cross-tabulated results of article counts coded as *Course Level* or *Academic Success*. Codes not mutually exclusive. [a]

		Academic Success					
		Freshman	Gender Related	Persistence	Self-efficacy	Performance (Follow-forward)	Student Engagement
Course Level	Freshman/ Sophomore	3	1	1	2	4	15
	Junior/Senior	0	0	0	1	2	2
	Graduate	0	0	0	0	1	2

[a] Count of mutually exclusive articles equaled 17.

The first dimension of our WoE framework was the mean *soundness of study* ($\bar{x}_S$) for each article. This was calculated using Equation (1) and appraised the quality of each study's methodology with the questions *1a – 1e* (Table 2.4). Individual scores (x_i) for these questions ranged from 1 (poor) to 3 (excellent).

$$\bar{x}_S = \frac{\sum x_i}{n} \tag{1}$$

The next two dimensions, *appropriateness of study* (x_A) and *relevance of study* (x_R), were based on question *2a* and question *3a*. These again were scored on a scale of 1 (poor) to 3 (excellent) and looked at how appropriate each study was at answering and aligning with our research question.

We calculated a composite quality score (Q_{CS}) using Equation (2). This equation weighted x_A and x_R by 150% because of the importance of these dimensions over that of $\bar{x}_S$. This guarded against individual articles receiving high overall Q_{CS} values while exhibiting marginal x_A and x_R scores.

$$Q_{CS} = \bar{x}_S + 1.5(x_A + x_R) \tag{2}$$

Table 2.4
Quality appraisal rankings indicating the quality of each study relative to the research question (author identities anonymous to mitigate criticism).

Study (Author names removed for propriety)	1. Soundness of study					2. Appropriateness of study	3. Relevance of study	Composite Quality Score (Q_{CS})	Mean (Group)	Standard Deviation (Group)	Quality Ranking [a]
	a. Are the aims and objectives of the research clearly stated?	*b.* Is the research design clearly specified and appropriate for the aims and objectives of the research?	*c.* Do the researchers provide a clear account of the process by which their findings were reproduced?	*d.* Do the researchers display enough data to support their interpretations and conclusions?	*e.* Is the method of analysis appropriate and adequately explicated?	*a.* Is the research design appropriate to answer review research question?	*a.* How well is the study matched to the review research question?				
1	3	3	3	3	3	3	3	**12.0**	11.16	0.90	High
2	3	3	3	3	3	3	3	**12.0**			
3	3	3	2	3	3	3	3	**11.8**			
4	2	3	3	3	3	3	3	**11.8**			
5	3	1	3	2	3	3	3	**11.4**			
6	3	3	1	3	3	2	3	**10.1**			
7	3	3	2	3	2	2	3	**10.1**			
8	2	3	3	3	2	2	3	**10.1**			
9	2	3	1	3	3	3	2	**9.9**	8.76	1.28	Medium
10	3	3	2	2	2	2	3	**9.9**			
11	3	3	1	2	1	3	2	**9.5**			
12	3	2	1	1	1	2	3	**9.1**			
13	3	3	2	2	2	2	2	**8.4**			
14	3	3	1	3	1	2	2	**8.2**			
15	3	2	1	1	2	1	2	**6.3**			
16	3	2	2	3	3	1	1	**5.6**	5.40	0.28	Low
17	3	1	3	3	1	1	1	**5.2**			
								Overall:	9.49	2.17	

[a] See Table 2.5 for Quality Ranking thresholds.

Delineating between high, medium, and low-quality articles, as indicated in Table 2.5, was accomplished by calculating the lower threshold value limits (TVL_i) for each ranking. This was done using Equation (3),

$$TVL_i = o + (r * Q_i) \tag{3}$$

where Q_i is the 25%, 50%, and 75% quartiles respectively, o is the lowest possible Q_{CS} values offset (o = 4), and r is the range between highest and lowest possible Q_{CS} values

($r = 8$). To better support our threshold limits, compared to other methods found in the literature, we used these quartiles to rank the quality of each article. As **Error! Reference source not found.**indicates, eight of the 17 studies ranked as high quality, which we used in our in-depth synthesis and conclusions.

Table 2.5
Rank and threshold values used in quality appraisal.

Rank	Lower TVL	Upper (TVL)	Quartile
High	≥10.0	≤12.0	75%
Medium	≥ 6.0	<10.0	50%
Low	> 0.0	< 6.0	25%

Synthesis

We performed a line-by-line evaluation of the full-text of the eight high quality studies, which constitutes a thematic and analytical synthesis of the literature. The former is presented by using a coding structure that generalized themes across studies to form a common language with which to support our analytical synthesis (Gough et al., 2012). This analytical synthesis constitutes the original knowledge of our review and attempts to illustrate "what it all means" when considering influences of mechatronics on student engagement in fundamental engineering courses. A descriptive summary of the eight high quality studies is first presented to inform the analytical conclusions of our synthesis (Borrego et al., 2014).

Description of Literature

We present a description of each study in Table 2.6. By presenting this we give full disclosure to our methods and results in an attempt to strengthen the conclusions of our review (Borrego et al., 2014). Also, we abbreviated the study authors and citations with the letters A through H for brevity, which can be cross-referenced in Table 2.6.

Table 2.6
Description of setting, students, course, and content of high quality studies.

Study	Abbr.	Institution	Country	Class Size	Required Course?	Major s Only?	Platform Selection	Programming Language	Activity Type
Bolanakis, Glavas, & Evangelakis, 2007	A	Epirus Educational Institute of Technology, Arta Department of Communications, Informatics and Management	Greece	Unknown	Unknown	No	Custom microcontroller board with Freescale MC68HC908GP32	C Assembly	Laboratory Activities
Verner & Ahlgren, 2004	B	Trinity College Department of Engineering	United States	~20	No	Unknown	Custom & off-the-shelf designs w/ Lego Mindstorm kit (NXT language) Handy-Board microcontroller	Interactive-C	Contest
McLurkin, Rykowski, John, Kaseman, & Lynch, 2013	C	Rice University Department of Computer Science	United States	Unknown	Yes	Unknown	Customized robot (Rice r-one) platform Texas Instruments LM3S8962 Stellaris microcontroller	C/C++ Python	Laboratory Activities
Nedic, Nafalski, & Machotka, 2010	D	University of South Australia School of Electrical and Information Engineering	Australia	~200	Yes	Unknown	Student-assembled power supply, student-assembled microcontroller w/ Microchip PIC12F675 PICkit2™ Development Programmer/Debugger	N/A[b]	Project(s)
Durfee, 2003	E	University of Minnesota Department of Mechanical Engineering	United States	~200	Yes	Yes	Parallax BASIC Stamp microcontroller	BASIC	Contest
Castles, Zephirin, Lohani, & Kachroo, 2010	F	Virginia Tech, Blacksburg Department of Electrical and Computer Engineering	United States	>1,000	Yes	Yes	Tamiya 70097 twin-motor gearbox kit & custom electrical motor drive circuit	N/A	Laboratory Activities
Sarkar & Craig, 2006	G	Auckland University of Technology School of Computer & Information Sciences	New Zealand	Unknown	Unknown	Unknown	Microchip PIC16F84 microcontroller	BASIC	Project(s)
Troni & Abusleme, 2013	H	Pontificia Universidad Católica de Chile Department of Electrical Engineering	Chile	24[a]	No	No	Custom design w/ Savage Innovations' OOPIC microcontroller	BASIC C	Contest

[a] Picked by a selection process. [b] Software programming not used in this study.

Institution and Location

The eight high quality studies in Table 2.6 were spread across the globe, as indicated in Table 2.6. Four of these studies looked at student samples from institutions in the Northeast (B), South (F), Midwest (E) and Southwest (C) of the United States. The remaining studies were based in Greece (A), Australia (D), New Zealand (G), and Chile (H). This illustrates a diverse geographic sample of studies.

Class Size

The class sizes found in Table 2.6 ranged from 20 to 1,000 students. This is important to consider, especially when we discuss the theme of *Ease-of-Implementation* below. Class size can have a bearing on how "easy" it is to implement, monitor, guide, and evaluate PjBL and PbBL experiences. Interestingly, three of the eight studies (A, C, and G) did not publish class size information and one (H) used a selection process to enroll students into the course.

Required Course?

Four of the eight studies (C – E, and F) implemented mechatronic experiences in departmental required courses. In contrast, two studies (B and H) implemented mechatronic experiences into non-required courses, while two (A and G) did not report the curricular requirements of the course used in their study. Because non-required courses are selected based on student desires, the baseline student motivation level is likely to be higher than for required courses. Shell and Soh (2013) support this perspective when they found that a course's curricular requirement has an effect on student engagement levels. Because these studies did not indicate differences in engagement levels for different student sub-populations, further research is needed to understand these effects.

Major Students Only?

Similar to curricular requirements, Shell and Suh (2013) found a difference in engagement levels for major students compared to non-major students. Two studies (E and F) reported students to be homogenous to the major department offering the course, while two (A and H) indicated they were not. The remaining four studies (B – D, and G) did not publish this information. Due to the lack of clarity on this point, the overall effect of mechatronic experiences on non-major verse major students' engagement levels is unclear. Further research is needed to analyze these effects.

Platform Selection

A variety of platforms were found in the literature, spanning from fully customized designs in study C, to the off-the-shelf Tamiya 70097 twin-motor kits used in study F. Seven of the eight studies (A – E, G, and H) incorporated a microcontroller at the heart of their mechatronic platform. This is important when recalling the previous definition of mechatronics (Grimheden & Hanson, 2005), which does not indicate microcontrollers as a necessity. It is posited that the usage observed in these studies may support the notion that microcontroller knowledge and programming skills have become a ubiquitous element of mechatronic applications in academia.

Programming Language

Six of the eight studies (A – C, E, G, and H) required students to perform programming during the mechatronic experiences. This is interesting, as it illustrates how freshman and sophomore students can achieve a level of hardware and software integration usually reserved for junior and senior level courses. Furthermore, study B and study H allowed non-major students to enroll in the course. This speaks to the potential accessibility of this level of integration by even non-major students. In contrast, the remaining two studies (D and F) did not incorporate programming into their mechatronic experiences. Instead, they used a combination of mechanical and electronic assembly tasks (i.e., gear box, motor drive circuit, and printed circuit board assembly).

Moving beyond programming requirements, specific software languages were also highlighted. Predominantly, C and BASIC languages were used, with two studies (A and C) also exposing students to Assembly and Python. Interestingly, no study presented a clear rationale supporting their language selection, but we speculate these decisions were born out of convenience (i.e., the language(s) selected were familiar to the instructor or department) or the platform's requirements.

Activity Type

Three distinct activity types were found in the literature. These included laboratories, contest, and projects. When analyzing the three laboratory-based studies, F required two, C required bi-weekly, and A required weekly activities. It is interesting to recall that study F also did not require programming, while study A and study C did. This could indicate a connection between the increased complexity of hardware and software integration and allowing student more opportunities to hone these skills.

In contrast to laboratory activities, three of the eight studies (B, E, and H) employed the challenge and pressure of a contest to motivate students to engage. One was a national level contest (B) and two were course contests (E and H). While two studies used highly competitive contests (B and H), one used a non-competitive design task exposition. Additionally, two of these studies (B and H) implemented this activity type in non-required courses and with small class sizes (~20 and 24, respectively), while the third was used in a required course with ~200 students. From this it appears contest can engage students in both required and non-required courses.

Lastly, two of the eight studies (D and G) used open-ended projects as the vehicle to solidify student learner outcomes. Between these, only study D identified whether the course was required and the number of students enrolled. While student surveys indicated positive effects on student engagement, this study reported an overwhelming effort required to implement mechatronic experiences in a large class, even with additional logistical and administrative support.

Thematic and Analytical Synthesis

Seven themes were identified in the literature from our analysis of the full-text of each study. These themes are tabulated in Table 2.7 which illustrates each study's contribution to our thematic synthesis. Five themes have been denoted as primary influences and two as secondary with respect to engaging students in fundamental engineering courses. Again, we restate primary influences as having direct effect on students and secondary influences as having effect on those responsible for implementing the experience. Not surprisingly, the most prevalent theme was *Student Motivation*, as this was central to our review question and used during our quality appraisal. In contrast, the least prevalent theme was *Gender*. In the following sections, we detail the contributions from each study to all seven themes.

Table 2.7
Contributions of high quality studies to synthesis themes.

	Themes						
Study	Student Motivation [a]	Self-Efficacy [a]	Rigor [a]	Accreditation [b]	Ease-of-Implementation [b]	Learning Retention [a]	Gender [a]
A	√			√			
B	√	√		√			
C	√		√			√	
D	√	√		√	√	√	
E	√	√			√		
F	√	√	√	√			√
G	√	√	√				
H	√	√	√		√		
Total	8	6	4	4	3	2	1

[a] Primary (i.e., having a direct influence on students). [b] Secondary (i.e., having an influence on those responsible for implementing experience.)

Student Motivation

This theme was found in all eight studies. It occurred in two distinct forms: 1) short-term (immediate) student motivation in course subject matter, and 2) long-term (projected) student motivation levels of students to pursue degrees in advanced STEM fields. Table 2.9 tabulates the quantitative results on student motivation we found in the literature, including notation distinguishing between the two distinct forms.

We first analyze short-term effect on student motivation. Study A concluded, using quantitative survey results on a 5-point Likert scale that, “students found the laboratory course inspiring” (2007, p. 796). Additionally, this study reported, “students emphasize that working with hardware increased their interest in the course” (2007, p. 796). Similarly, study C, collecting quantitative data from student surveys during the spring 2010 and spring 2011 semesters, concluded mechatronic experiences “helped students solidify what their ideas of engineering entailed and how STEM subjects are integrated in all aspects of their lives” (2013, p. 29). Looking at Table 2.9, the percentages of “agree” and “strongly agree” declined; they did, however, comment that this was due to extensive travel time by the instructor. Study F (with the largest class size; *n* > 1,000), again using self-reporting surveys, found most of students perceived the overall mechatronic experience to be "good" or "excellent". Anecdotally, study G concluded that student motivation improved because of the experience. The authors expressly report, "We observed that by participating in the PIC-based projects and demonstration activities, students became increasingly motivated to learn more about computer hardware and enjoyed this course more than previous courses that consisted of lectures only" (2006, p. 160). From this evidence, it appears that students were highly motivated by and towards mechatronic experiences in the short term.

Mechatronic experiences also exhibited long-term effects on student motivation. Study C expressed that mechatronics "helped to increase [students'] desire to major in a STEM field" (2013, p. 29). However, a decline in student motivation, as seen by responses of "agree" or "strongly agree", was evident in this study from 2010 (85%) to 2011 (69%). The reason for this decline, as stated above, was attributed to extensive travel time by one of the instructors. Similarly, in study D, a majority of students selected "agree" or "strongly agree" to the question: "The laboratory project has motivated me to learn more about electrical engineering" (2010, p. 391). Study B concluded, based on qualitative observations, the mechatronic experience "elicited a strong, positive student reaction" (2004, p. 200). Quantitatively in Table 2.9, this study also found 100% of survey respondents indicated a "strongly positive" or "limited positive" student motivation from the mechatronic experience toward pursuing "science and technology subjects", and 80% indicated a "strongly positive" or "limited positive" student motivation from the experience to enter "an advanced level engineering programme"

(2004, p. 199). Again, mechatronic experiences were reported to crystalize many students' desire to select engineering undergraduate programs of study. Study E specifically stated, "many students comment[ed] that the Robot Show solidified their commitment to engineering" (2003, p. 596). Contrary to these findings, study A found students did not "appear sufficiently motivated to want to become involved with microcontrollers, microprocessors, embedded systems, etc. in the future" (2007, p. 796). This negligible student motivation in study A was concluded to be a function of the participating students' career goals, which overwhelmingly were towards software engineering. This supports Jones, Paretti, Hein, and Knott's (2010) findings on the effect of student career goals and perceived alignment to course content on long-term student motivation. This study also found students did not "believe they acquired the ability to use the microcontroller in future applications" (2007, p. 796). The authors concluded this to be due to the introductory nature of the course in question. Apart from the contradictory results of one study, the literature indicates that mechatronic experiences lead to most of students exhibiting increased levels of short-term and long-term student motivation.

Table 2.8
Select study results for mechatronic experiences and self-efficacy.

Study B (*n* = ~20)	*Percentage of Students Increasing in Self-Efficacy*	
Dimension of Course Content	Theory	Practice
Electronics, computer comm., motors/gears, mechanical design, controls, sensors	100%	100%
Systems design	90%	100%
Microprocessor, high-level language	90%	89%
Mathematical modeling	90%	78%
Data analysis, teamwork practice	80%	89%
CAD tools	60%	67%
Physical fields	60%	44%
Assembly language	60%	22%

Study D (*n* = ~200)	*Percentage of Student Responses*	
	Elec. Eng. Students	All Students
Survey Questions	Agree + Strongly Agree	Agree + Strongly Agree
"The laboratory developed my understanding of concepts and principles in electrical engineering?"	85%	80%
"I am satisfied that I acquired useful knowledge and skills in electrical engineering"	85%	67%

Scale: 9-point Likert (labels un-reported)

Study F (*n* = >1,000)	*Percentage of Student Responses*
Survey Questions	Yes
"Did building this circuit give you a better understanding of electrical circuits and their use in applications?"	~45%

Scale: Poor, Average, Good, Excellent

Study G (*n* = Unknown)	*Percentage of Student Responses*
Survey Questions	(4) + (5)
"How effective were the PIC-based project demonstrations in helping you to improve your understanding of computer hardware concepts?"	75%

Scale: Poor (1), Excellent (5)

Study H (*n* = 24)	*Students' Responses to Skills Improvement*		
Dimensions of Course Content	Pre-course	Post-course	Difference
Designing and programming mechatronic systems	3	6	3
Mechanical design	4	6	2
Electrical design	5	7	2
Implementation of the real problems in engineering	5	7	2

Scale: 10-point Likert (labels un-reported)

Self-Efficacy

Six of the eight studies we analyzed reported increases in self-efficacy in technical content after conducting a mechatronic experience. Five of these reported quantitative results, as listed in Table 2.8. Of these, four (B, D, G, and H) reported strong effects, as evidenced by high percentages of students indicating positive results from the mechatronic experience on understanding and retaining mechanical, electrical, and programming content. In contrast, study F reported marginal effects on self-efficacy, using self-reporting surveys. Interestingly, laboratory activities were used in this study, in contrast to those reporting strong effects on self-efficacy, which used contest and projects. Further supporting the connection between contest and self-efficacy, study E reported increases in students' confidence in their ability to design and build functioning mechatronic devices. The accomplishments experienced through this contest crystalized some students' decision to pursue engineering fields.

From the findings in these five studies, it appears there is a positive connection between mechatronic experiences and self-efficacy in technical content, specifically when a contest is employed. This, however, contradicts Deming's remarks in *The New Economics For: Industry, Government, Education,* where he states, "…competition, we see now, is destructive. It would be better if everyone would work together as a system, with the aim for everybody to win…Competition leads to loss" (2000, p. xv). Further research is called for, which more fully examines the specific interaction effects of competition verses non-competition activities on self-efficacy. Conflicting results were found in the literature with very different methods, which further confounded the outcomes.

Table 2.9

Select results of long-term influences of mechatronic experiences on motivation.

Study A (*n* = Unknown) *Survey Questions*	*% Students Responding "Much" + "Very Much"*
"Did the computer architecture laboratory inspire your interest for the course concerning other laboratory courses you have attended?" [a]	62%
"Do you believe that working with hardware during the lessons increases the interest for the course?" [a]	62%
"Did the laboratory course motivate you to involve with similar issues (much, mP, embedded systems, etc.)?"	21%
"Did the laboratory course provide you the ability to involve with microcontroller applications in the future?"	23%

Scale: Not at all (1), Shortly (2), Enough (3), Much (4), Very Much (5)

Study B (*n* = ~20) *Survey Questions*	*% Students Responding "Limited Positive" + "Strongly Positive"*
Student motivation from the mechatronic experience toward pursuing "science and technology subjects"	100%
Student motivation from the mechatronic experience to enter "an advanced level engineering programme"	80%

Scale: Negative Impact, No Contribution, Limited Positive, Strongly Positive

Study C (*n = Unknown)*	*% Students Responding "Agree" + "Strongly Agree"*	
Survey Questions	2010	2011
"Helped me figure out what engineering really is." [a]	94%	73%
"Helped me recognize applications for my basic math and science courses in engineering problems." [a]	93%	60%
"Improved my familiarity with several areas of engineering." [a]	100%	99%
"Increased my desire to select an engineering major."	85%	69%

Scale: 5-point Likert (labels un-reported)

Study D (*n* = ~200)	*% Students Responding "Agree" + "Strongly Agree"*	
Survey Questions	Elec. Eng. Students	All Students
"The laboratory project has motivated me to learn more about electrical engineering."	95%	73%

Scale: 9-point Likert (labels un-reported)

Study F (*n* = >1,000) *Survey Questions*	*% Students Responding "Good" + "Excellent"*
"How would you rate your overall experience?" [a]	67%

Scale: Poor, Average, Good, Excellent

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[a] Short-term effects.

Course Rigor

Four of the eight studies (C, F – H) indicated increases in course rigor (e.g., level of effort, time) after implementing mechatronic experiences. Study C reflected that increasing the rigor of a class with technical, hands-on mechatronic experiences helped students make deeper and broader connections between diverse engineering fields. Study F, looking at mechanical and electrical content, found students perceived the latter to be more rigorous while exhibiting no significant difference in their enjoyment level between either. Study G, using self-reported surveys, found roughly 70% of students felt "satisfied" with the rigor and hands-on aspects of the mechatronic experience. Finally, study H reported qualitatively that the most prevalent comment by students was that the mechatronic experience demanded significantly more than the course suggested 10 hours per week. Even so, student evaluations were positive and indicated they perceived the course was a constructive experience in problem solving. These results indicate that mechatronic experiences have the potential to increase the rigor of a class without sacrificing student satisfaction and enjoyment.

Accreditation

Explicit connections between mechatronic experiences and accreditation standards were made in four of the eight studies (A, B, D, and F). These studies, listed in Table 2.10, indicated the potential of mechatronic experiences to satisfy both ABET and Engineers Australia (EA) standards regardless of activity type or programming requirement. These studies indicated that the hands-on, multi-disciplinary problem-solving nature of these experiences lends them to satisfying a diverse range of hard (i.e., mathematics and problem-solving) and soft (i.e., teamwork and ethics) accreditation learning outcomes.

Table 2.10
Connection between mechatronic experiences and accreditation body standards.

Accreditation Board of Engineering and Technology			Engineers Australia
Verner & Ahlgren, 2004	Castles, Zephirin, Lohani, & Kachroo, 2010	Bolanakis, Glavas, & Evangelakis, 2007	Nedic, Nafalski, & Machotka, 2010
Ability to apply knowledge of mathematics, science, engineering	Instrumentation [a]	Solving engineering problems	Exhibit skills necessary to practice in complex environments
Ability to design a system, component, process	Models [a]		
Ability to function on multidisciplinary teams	Design [a]		
Ability to identify and solve engineering problems	Learn from failure [a]		
An understanding of professional and ethical responsibility	Safety [a]		
Ability to apply techniques, skills, and modern tools	Teamwork [a]		

[a] Based on ABET and Sloan Foundation colloquy on laboratory learning objectives (Feisel & Peterson, 2002).

Ease-of-Implementation

Extensive discussions concerning the effort required to implement mechatronic experiences into a course were included in three of the eight studies (D, E, and H). These comments covered the spectrum, ranging from extensive effort to marginal effort. Specifically, study D found the initial implementation of a mechatronic experience to be overwhelming, due to a lack of faculty/staff qualifications and availability. To reduce this strain, improvements were implemented based on student and faculty input. Additionally, pre-semester training in areas of technical and pedagogical issues was conducted to bolster the success of the experiences. In contrast, study E posited that implementing mechatronic experiences in fundamental courses, even those with large enrollments, could be accomplished with only “modestly more” effort (2003, p. 593). To support this stance, the study presented activities, logistical considerations, and lessons-learned to enable mechatronic experiences to flourish within a course. Study H fell between these two extremes by presenting course content examples and team building considerations to enhance both the quality of students’ projects and the depth of their inter-personal team skills.

Comparing study D (overwhelming effort) and study E (marginal effort), Table 2.6 illustrates similar class size and course requirements. The difference in effort arises from activity type and programming requirements. Study D used open-ended project activities without requiring programming, while study E employed a contest requiring programming. Here, we feel the weight of the difference falls on the activity type and not the requirement of programming. As open-ended projects with dissimilar outcomes are much harder to manage, having a common contest rubric applied to all students can streamline the implementation effort. Also, a contest can allow for a more focused and congruent presentation of course content that culminates in common objectives for all students.

Learning Retention

Two of the eight studies (C and D) reported positive effects of mechatronic experiences on learning retention. We define “learning” to include knowledge and skills. Study C qualitatively observed mechatronic experiences “are an effective way to…train students in STEM topics” (2013, p. 24). Here, the word “train” was used to describe knowledge acquisition. Specifically, when piloting a mechatronic experience to a class of United States Military Academy cadets, this meaning was used to discuss how “a deeper retention of the sensor knowledge” was observed in students (2013, p. 30). Exam scores after the experience were almost 18% higher compared to exam scores following lectures using improvised explosive devices (IED) teaching aids. Similarly, study D highlighted learning retention by saying, “…a project-based laboratory…improved students’ success rate.” (2010, p. 379) Here, “success” was used to describe the act of remembering skills and was found to be positively correlated to the use of mechatronic experiences. This study based these findings on self-reporting surveys. From these studies, mechatronic experiences have been found to have a positive effect on learning retention in fundamental engineering courses.

Gender

Study F was the only study to consider the effects of mechatronic experiences on student engagement of females. Here, hands-on experiences were expressly intended to engage women and increase their interest in the fields of mechanical, electrical, and computer engineering. Based on student survey results, the authors observed the overall perception of these experiences by female students to be positive. This positive perception, and the level of student learning received from the experience, were not significantly different between males and females. However, a lower percentage of females possessed prior experience related to mechatronics content, and female students required slightly longer durations to complete activities within the experiences. The long-term effects of increased interest in mechanical, electrical, and computer engineering were not reported. Based on our inability to find other high-quality research specifically analyzing the effects of mechatronic experiences on gender, this is a clear topic for future research.

Discussion

A Note on Meta-Analysis

For two reasons, our review does not include a rigorous statistical meta-analysis. First, as Petticrew and Roberts advocate, “Perhaps the least useful way of dealing with qualitative data in systematic reviews is to turn it into quantitative data” (2008, p. 191). Because a large fraction of results were qualitative in nature, we were hesitant to quantize them. Second, most of the research designs and results were insufficiently consistent to warrant a meta-analysis. Therefore, we employed a more narrative qualitative content analysis when synthesizing the results.

Considering the variability in methods and consistency of reporting found in the literature, we recommend a more consistent methodology for future efforts in this field. Specifically, methodologies that measure effects with pre-treatment verse post-treatment and/or control verse treatment groups are encouraged (Leedy & Ormrod, 2013). Of the studies reviewed, only study H used this level of rigor. Also, we would encourage a more consistent structure in reporting research findings. Similar to the endorsement of detailed methods for systematic reviews in engineering education by Borrego, Foster, and Froyd (2014), we endorse the use of standardized reporting schemes, such as Schulz, Altman, and Moher’s (2010) CONSORT or von Elm *et al.’s* (2014) STROBE check lists. Both schemes intend to present findings in a transparent and consistent manner. By using the items (as appropriate) within these reporting standards will promote a common language across research specific to mechatronics, and engineering education. Improving the structure of reporting in these fields should also enable deeper and broader qualitative and quantitative syntheses in the future.

Robustness of Synthesis

Analyzing the robustness of our synthesis, we first point to the transparency of our review methods. As Borrego, Foster, and Froyd (2014, p. 63) suggest, “The quality of a systematic review is determined primarily by consistency and transparency in selecting and reporting procedures for every step of the review.” In other words, the conclusions reached by our synthesis can be judged effectually by how well we presented our methods. The following questions can be asked about our results and were borrowed from Gough, Oliver, and Thomas,

- “Do the results vary according to the quality of the studies contributing?
- Should any issues about [the studies’] quality affect the strength and credibility of the synthesis?
- Do the results depend heavily on one or two studies, in the absences of which they would change significantly?
- Which contexts can the results be applied to?” (2012, p. 189)

Answering questions one and two, we point to our quality appraisal, which ranked all 17 relevant articles as low, medium, or high quality. Based on this appraisal, we synthesized results from only high-quality studies, attempting to normalize the variability in quality and removing concerns of strength or credibility. Looking at Table 2.4, the high-quality articles had a mean Q_{CS} value of 11.16 with a standard deviation of 0.90. Based on this, we feel limited issues of variability and strength exist in our results.

We use the frequencies of each theme in Table 2.7 (as depicted by its bottom row) to answer question three. It is evident that the themes of *Student Motivation* and *Self-Efficacy* are reinforced by most of the studies. Therefore, these are considered very robust themes in the literature. Looking at *Course Rigor, Accreditation,* and *Ease-of-Implementation*, roughly half the studies demonstrated these, indicating them to be intermediately robust. The remaining themes of *Learning Retention* and *Gender* are represented in two and one study, respectively, indicating a lack of robustness. However, these last two should not be completely discredited, as they represent key areas for future research towards understanding the influences of mechatronic experiences and student engagement in fundamental engineering courses.

To answer the fourth and final question, we point to the intent of our review. It forms the context from which our synthesis results should be viewed. Specifically, our results should be applied to efforts towards engaging freshman and sophomore engineering students through mechatronic experiences, as this was the focus of our review question.

Relevance to Research Question

The primary goal of our research has been to answer the question: "What are the primary and secondary influences of mechatronic experiences on student engagement in fundamental engineering courses?" From our review, we have synthesized five primary (directly affecting students) and two secondary (affecting those responsible for implementing the experience) themes (Table 2.7). These seven themes illustrate how mechatronic experiences can influence student engagement in fundamental engineering courses.

Primary Influences

Of the eight studies we analyzed, the findings in each indicated a strong link between mechatronic experiences and students exhibiting high levels of short-term and long-term student motivation towards technical content and STEM fields. It is important to note study A found conflicting results on long-term student motivation towards STEM careers. The juxtaposition of these results illustrates the effect that students' existing career goals can have on long-term student motivation (Jones et al., 2010). It also highlights an important aspect of the literature, which shows that positive effects on long-term student motivation are heavily governed by students' existing career goals. It can therefore be positively influential to introduce students to the diverse nature of engineering through mechatronic experiences early in their education. This can give them an increased understanding of the multi-disciplinary and related fields of engineering, which help them make more informed career decisions, as stated by study F.

Considering the influences of self-efficacy, five of the eight studies (B, D, E, G, and H) reported strong positive effects of mechatronic experiences on self-efficacy in technical content, while study F found weak effects. It is interesting that the study to report weak results used laboratory activities, while the others used contests and project(s). This does not prove causation that laboratory activities produce weak positive self-efficacy in students. It merely presents the observed differences that activity types can have on students.

Four of the eight studies (C, F – H) reported an increase in course rigor through implementing mechatronic experiences. It was also found that this increase in course rigor was not at the sacrifice of student satisfaction or enjoyment. Additionally, deeper and broader connections between diverse technical fields were fostered in students using these complex activities.

The literature also illustrates mechatronic experiences to increase learning retention. Two of the eight studies (C and D) found students possess higher level of knowledge and skills retention when exposed to mechatronic experiences.

As indicated in our synthesis, only study F reported influence on underrepresented females in STEM fields. This disparity in the literature highlights the need for increased research into the effects of mechatronic experiences on gender diversity in technical programs. However, we found mechatronics can engage females and males equally. The extent to which it draws increased numbers of females to technical fields is still unknown.

Secondary Influences

In four of the eight studies (C – E, and G), it was evident that mechatronic experiences can serve programs in meeting a diverse set of accreditation outcomes. The robustness and diversity that mechatronic experiences hold for engaging students in hard (i.e., mathematics and problem-solving) and soft (i.e., teamwork and ethics) skills should be appreciated. These skills are directly applicable to the accreditation standards of bodies such as ABET and EA, and were identified by four of the eight studies (A, B, D, and F).

Lastly, three of the eight studies (D, E, and H) commented on the level of effort necessary to implement mechatronic experiences. These remarks ranged from extensive to marginal logistical efforts. Evaluating these extremes, it was striking to observe the main difference arose in activity type. Study D reported overwhelming logistical effort while using open-ended projects. In contrast, study E reported marginal effort while using a contest. This seemingly points to the increased logistical effort necessary to manage open-ended mechatronic projects. This can be especially appropriate when initially implementing this teaching strategy in large fundamental engineering courses.

Limitations and Future Work

The literature we have analyzed is rich and full of meaningful results. Even so, there were limitations in these studies that deserve further research towards solidifying a coherent list of influences of mechatronic experiences relative to engaging freshman and sophomore students in engineering. First, it was unclear from the literature how mechatronic experiences effects student engagement when considering the factor of required verse non-required course. Closely related to this was the effect that the factor of non-major verse major has. Also, it was unclear from the literature what effect that activity type (e.g., laboratory, project, or contest) has had on self-efficacy. Moreover, limited evidence was found on the effects of these experiences on learning retention, gender inclusion, and ease-of-implementation.

Most notably was the lack of clear pre-treatment verse post-treatment or control group verse treatment group research designs presented in the literature. Study H did provide this level of methodology, but additional research is needed to bolster these findings.

Limitations in our own review exist. First, our search strategy has inherent limitations in that it was not capable of collecting 100% of all articles related to our topic (e.g., conference proceedings). Especially related to this was our decision to not include the term “robot” and its variations. Second, we relegated our synthesis to only high-quality articles. This may have unintentionally introduced publication bias into our findings, as high-quality articles are more likely journal articles, which may have tendencies to publish positive results over null results. Third, some of our exclusion criteria may have led to rejection of valuable literature (i.e., non-English articles). Finally, we were limited by which themes were reported in the articles. Some themes may be more (or less) significant than what we have reported. Considering these limitations, we have attempted to be as rigorous and equitable in our review as possible, understanding that our research is an attempt to define a swath of literature that is broad and multifaceted.

Conclusion

In our review, we have presented the methods used to systematically select, collect, and evaluate literature that speaks to the effect of mechatronic experiences on student engagement. These results were synthesized to reveal five primary and two secondary themes, each demonstrating positive influences. From this synthesis, we found overwhelming evidence that these experiences increase student motivation, self-efficacy, and course rigor. There was also evidence of positive effects on learning retention, gender diversity, accreditation efforts, and course content implementation.

We feel our conclusions serve a wide range of engineering educators, as mechatronics integrates a diverse set of technical fields. By using a systematic review methodology, we have highlighted the influential breadth and depth of mechatronics with the intent of augmenting other’s efforts towards increasing student engagement.

Considering the observed benefits of mechatronic experiences to positively engage students, we make these final comments:

- Mechatronic experiences can be uniquely beneficial in fundamental courses, as they help students see multi-disciplinary connections in engineering fields.
- Mechatronic experiences will most likely increase the rigor of a course without sacrificing student satisfaction and enjoyment.
- Open-ended design projects have been found to be the most demanding activity types to use when implementing mechatronic experiences, especially for the first time and in fundamental courses.
- When requiring programming as part of mechatronic experiences, frequent laboratory exercises can also be beneficial.
- Existing student career goals, which are often intrinsic to students, may diminish the effects of mechatronic experiences on student engagement.

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CHAPTER 3. QUANTIFYING DIFFERENCES IN MOTIVATIONAL ORIENTATION AND ACADEMIC SUCCESS IN A MECHATRONIC EXPERIENCE

Manuscript to be submitted to the *Learning and Instruction*

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Abstract

Many have theorized strong links between academic success and student motivation. Still others have indicated the ability for mechatronic experiences to influence student motivation. However, limited research has rigorously examined how it changes motivation and academic success. The purpose of this study was to empirically quantify differences in undergraduate students' motivational orientation and academic success in a mechatronic experience vs. a non-mechatronic experience. Using a quasi-experimental, non-equivalent control vs. treatment design (n=84) we found no statistically-significant difference in students' motivational orientation – specifically *value choices* [$F(6,77)=0.13$, $p=0.7224$] and *expectancy beliefs* [$F(6,77)=0.38$, $p=0.5408$] – between mechatronic and non-mechatronic experiences. In contrast, statistically-significant increases in project scores [$F(5,78)=6.51$, $p=0.0127$, $d=0.48$,

$d_{95\%CI}$=0.00 – 0.98] and final course grades [$F(5,78)=7.76$, $p=0.0067$, $d=0.70$, $d_{95\%CI}$=0.20 – 1.20] were observed in the mechatronic experience group, (three and eight percentage points, respectively). Even though these findings help explain differences in motivational orientation and academic success associated with mechatronic experiences, future research is needed to further understand the nuanced dynamics of motivational orientation within a mechatronic experience.

Keywords: motivation; academic success; mechatronics; engineering education

Introduction

Student motivation is considered "sensitive to context" and "…schools can make changes in the learning environment that increase the number of students who stay engaged and motivated…" (Meece, 1997, p. 7). Real-world projects and activities in the classroom have the potential to motivate students to engage with learning (Pintrich, et al., 1993). In engineering/technology classrooms, mechatronic experiences have been found to enhance students motivation and learning (Castles et al., 2010; Durfee, 2003; McLurkin et al., 2013; Nedic et al., 2010; Verner & Ahlgren, 2004). Here, we define mechatronics as the "synergistic combination of precision mechanical engineering, electronic control and systems thinking in the design of products and manufacturing processes" (Grimheden & Hanson, 2005, p. 180). With the multi-disciplinary nature of these experiences, it is not surprising that they have been implemented in a variety of science, technology, engineering, and mathematics (STEM) curricula (especially the electrical, mechanical, and computer fields). A recent systematic review examined the influence of mechatronic experiences on student engagement and found positive influences on student motivation and self-efficacy (Haughery & Raman, 2016). However, gaps in the literature were highlighted in this review. Specifically, the review found limited usage of control vs. treatment or pre- vs. post-test research designs, limited explanation of experimental methods, only preliminary descriptive statistics of quantitative results, or anecdotal examples of qualitative findings (Haughery & Raman, 2016). While these results indicate that there is some quantitative and qualitative evidence that supports the motivational value and academic benefit of mechatronic experiences, stronger, more detailed evidence is needed to more fully validate these premises.

Research Objective and Questions

Our objective was to quantify the differences in undergraduate students' motivational orientation and academic success for a mechatronic experience vs. a non-mechatronic experience. To accomplish this, we asked the following research questions,

1. Did students in the treatment group have different levels of motivational orientation and academic success compared to those in the control group?
2. Was there a difference in the proportion of students who reported being motivated in the treatment group compared to the control group?
3. What was the relationship between students' motivational orientation and academic success, and did it differ in the treatment group vs. the control group?

Academic Success Definition

According to Meece, “The goal of any educational program must be to create a learning environment that supports or elicits students’ intrinsic interest in learning” (1997, p. 34). While many would argue that achieving a certain level of learning equates to academic success, York, Gibson, and Rankin (2015) found this term poorly and ambiguously defined in the literature. In an attempt to bring clarity, they used a grounded theory approach to synthesize a high-level, six-faceted framework of academic success to include *academic achievement* (e.g., grades and GPA), *satisfaction* (e.g., college/course experience), *attainment of learning outcomes* (e.g., student engagement and proficiency profile), *persistence* (e.g., graduation rates, retention), *career success* (e.g., job attainment rates, salary, and career satisfaction), *acquisition of skills and competencies* (e.g., critical thinking and problem solving). This conceptual model was based on a review of over 30 sources of literature (York et al., 2015). Also examining these facets, von Strumm, Hell, and Chamorro-Premuzic (2011) found student intelligence (i.e., cognitive ability) to be one of the single strongest predictors of academic success. They also reported the interaction effects between student effort and student intellectual engagement (i.e., intellectual curiosity) to predict academic success to a similar degree as intelligence. Light (1992, 2004) denoted student engagement (i.e., student involvement in learning) as a critical factor in educational development, while Kamphorst, Hofman, Jansen, and Terlouw (2015) indicated it as pivotal to student persistence. Wilson *et al.* (2014) postulated that student engagement is an intermediate outcome to academic success that is evident in students sooner than the six facets proposed (2015). Nelson *et al.* (2015), suggest student engagement to be directly proportional to learning achievement. Taking a slightly different perspective, Pike (1999, 2000), Pike and Killian (2001), and Gellin (2003) found student motivation can have a vigorous and positive relationship with student engagement. Similarly, Pintrich, Smith, García, and McKeachie (1993) suggest engagement to be a function of student motivation. They indicate that students' motivational beliefs affect cognitive engagement. It is evident that a link exists between academic success and motivation.

Motivation Theory

Considering motivation, Meece defines it as the "desire to work and learn" (1997, p. 5). Clark, borrowing from the work of Bandura (1997), defines motivation as "…the amount and quality of the 'mental effort' people invest in achieving goals" (1998, p. 2). Pintrich and Schunk defined motivation as "…the process whereby goal-directed activity is instigated and sustained" (1996, p. 4). From these complimentary definitions, the multifaceted nature of motivation begins to emerge. Therefore, it is helpful to further delineate the complex factors that affect student motivation.

One perspective of motivation is Clark's *Choice and Necessary Effort* (CANE) model. In this framework, he described how an individual's commitment to, or motivation towards, a goal is affected by *goal choice* and the *effort* needed to reach that goal. Clark (1998) hypothesized that these two components are continually re-examined to regulate an individual's level of motivation towards a goal. The first component, *goal choice*, is strongly affected by the factor of *goal value*, which is comprised of *utility* (i.e., the usefulness of a task in light of future goals) (Pintrich & Schunk, 1996), *interest* (i.e., the enjoyment or intrinsic inquisitiveness towards a task), and *importance* (i.e., the significance of succeeding in a task). The second part, *effort*, is strongly affected by *task* *assessment*. This factor is comprised of *self-efficacy* (i.e., Can I do it?), and *personal agency* (i.e., Will I control my destiny?). Finally, positive and negative mood characterizes *emotion*. Positive mood is directly proportional to goal commitment while negative mood is inversely proportional (Clark, 1998).

From an expectancy model perspective, Bandura (1997) proposed that an individual's motivation is affected by one's beliefs of *self-efficacy* and *control of outcomes* (i.e., Do I have control of my success or failure?). In this expectancy model, the component of self-efficacy is dissected into two distinct elements: 1) outcome expectations (i.e., the belief that one's behaviors affect outcomes), and 2) efficacy expectations (i.e., the belief that ones' behaviors can be effectively performed) (Bandura, 1994). Wilson *et al*. (2014) further aligned self-efficacy theory with student engagement. They state that the strength of engagement is directly proportional to the strength of the belief that students have in their ability to accomplish a task. Many more suggest that self-efficacy is a strong predictor of performance, persistence, and engagement (Halbesleben, 2010; Simbula et al., 2011; Vera et al., 2014; Xanthopoulou et al., 2007). Many classify student self-efficacy as a significant construct within the framework of student motivation (Bandura, 1997; Clark, 1998; Pintrich & Others, 1991; Pintrich & Schunk, 1996; Pintrich, et al., 1993).

Extending this, Pintrich, Marx, and Boyle (1993) combined *expectancy beliefs* with *value choices* and *meta-cognition* to form a *social cognitive* perspective of motivation. In their motivation-cognition model, value choices are comprised of *goal orientation*, *interest*, and *importance*; expectancy beliefs are comprised of *self-efficacy*, *attributions*, and *control beliefs*; and meta-cognition is comprised of *self-regulated* *learning*. This motivation-cognition model takes the perspective that meta-cognition and motivation form a symbiotic and dynamic relationship. A person continually evaluates intrinsic and extrinsic feedback to dynamically adjust their motivation towards learning (Schunk & Zimmerman, 2012). When this happens, a student is said to be self-regulating their learning (termed *self-regulated learning*), with the cognitive "energy" expended being labeled as *motivation* (Schunk & Zimmerman, 2012, p. 306). Self-regulated learning has been defined to include three primary phases: 1) *forethought* (including task analysis and self-motivated beliefs); 2) *performance* (including self-control and self-observed strategies); and 3) *self-reflection* (including self-judgment and self-reaction) (Schunk & Zimmerman, 2012, p. 375). As a person works through these phases, motivation determines the degree to which each later phase is performed, and subsequently the level of achievement that is reached. Therefore, motivation and academic success form a symbiotic relationship within a student's mental cognition.

Framework of the Research

The theoretical framework of this research is depicted by Figure 3.1. It illustrates the connections between student motivation, student engagement, academic success, and mechatronic experiences. Motivation and academic success constructs were included for clarity, as they are important to how we defined and measured these terms. The level to which students succeed academically has been linked to their level of motivation (Meece, 1997). This link is often mediated by students' level of engagement (Light, 1992, 2004), warranting its inclusion in this framework – solid arrows of Figure 3.1. Moreover, mechatronic experiences have been illustrated as tangible experiences that impact undergraduate engineering and technology students' motivation and academic success (see Chapter 2 findings) – dashed arrows of Figure 3.1. Specifically, the scope of our research was to quantify differences in student motivation and academic success in a mechatronic experience vs. a non-mechatronic experience.

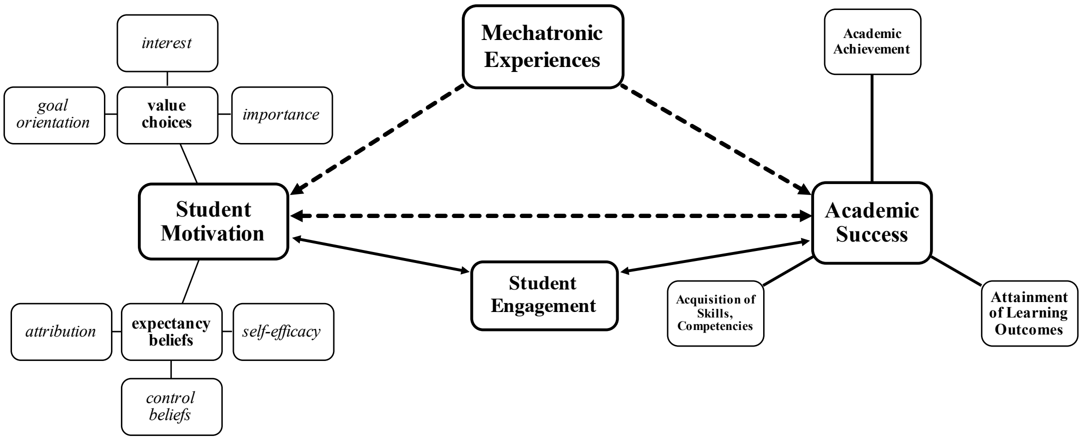

Figure 3.1
Theoretical framework of the relationship between mechatronic experiences, student motivation (Pintrich, et al., 1993), student engagement (Gellin, 2003; Light, 1992, 2004), and academic success (York et al., 2015), based on literature.

Materials and Methods

Quasi-Experimental Design

In our study, we used a quasi-experimental, non-equivalent control vs. treatment design (Trochim & Donnelly, 2001). The treatment group experience was administered during the spring semester of 2016, while the control group experience was conducted during the following fall semester. This multi-course implementation of our design mirrored others (Duncan & McKeachie, 2005) who have conducted similar motivation research using Pintrich and colleague’s (1991) *Motivated Strategies for Learning Questionnaire* (MSLQ). Furthermore, our “quasi” designation stems from the non-random assignment of participants to each experimental group (i.e., we had no control over which students were enrolled in which course section), as is common in educational research.

Treatment Group Experience

Treatment group students were asked to integrate the mechanical and electrical hardware of a robot with an original software program to autonomously navigate through a predefined maze. In the first four weeks of the project, they were individually responsible for completing five topic-centric activities (Table 3.1). These activities focused on software (program code) and hardware (motor and sensor) integration skills. With this foundation, they were given the last four weeks to develop, test, and implement their designs on the robot and course. The administration of this project was significantly informed by the methods and lessons learned from others (Bolanakis et al., 2007; Castles et al., 2010; Durfee, 2003; McLurkin et al., 2013; Nedic et al., 2010; Troni & Abusleme, 2013; Verner & Ahlgren, 2004). The hardware and software used in our mechatronic experience was an Arduino UNO microcontroller (Arduino, USA), ZUMO v1.2 robot (Pololu, Las Vegas, NV), and the Arduino 1.6.10 integrated development environment (Arduino, USA).

Control Group Experience

Our control group underwent the same instruction until week 10 and 11. At this point, instead of instruction in the physical function of sensor inputs and motor outputs, students worked through serial communication and character string parsing activities. During week 12 to 15, the control group was required to complete a final project that did not have mechatronic centric task requirements. Instead these students were required to solve three different data analysis tasks within the Arduino programming environment (e.g., determine the number of significant figures in a user defined number, sort user defined numbers in numeric order, and perform three predefined calculations while allowing the user to input unique variable values). Therefore, we intended to conduct the control group experience as similarly as possible. No mention of mechatronic content or topics were introduced or discussed with the control group. Furthermore, the same instructor taught both the control and the treatment groups' course sections.

Table 3.1
Detailed semester schedule of treatment group mechatronic experience.

Week	Week Topic	Project Requirements
8	Introduction, IDE, Structure Variables, Data Types	Complete five Mechatronic Activities
9	Arithmetic, Constants Flow Control, Switch Case, Break	
10	Digital & Analog I/O, Time	
11	Motor & Sensor Functions	
12	Challenge Task Development	Complete one of the Mechatronic Project challenge tasks in teams of four students 1. Manufacturing Part Delivery Task 2. Agricultural Harvesting Task 3. Animal Science Health Monitoring Task
13	Challenge Task Development & Testing	
14	Challenge Task Testing	
15	Challenge Task Completion/Presentation	
16	Finals Week	

Survey Sample Population

The theoretical population for our study was undergraduate students enrolled in fundamental engineering, engineering technology, technology, or applied engineering courses. Within this population, we focused on a convenience sample of *n*=84 undergraduate students enrolled in a technical problem-solving course, offered by the

Department of Agricultural and Biosystems Engineering at Iowa State University, Ames, IA. The term "fundamental course" was defined as a first-year class that occupied the core requirements of the department's Industrial Technology and Agricultural Systems Technology majors. Eighty-four percent were pursuing degrees within the department, while the remaining 16% were pursuing a range of degrees in agricultural business, agricultural exploration, agricultural studies, agronomy, and food or animal science. Male/female splits were 92% to 8% (compared to our department's typical 95% to 5% split), respectively, while the ethnicity split was of 91% non-underrepresented (i.e., White/Caucasian) students to 11% underrepresented students (compared to our department's typical 10%). Furthermore, students 18 – 19 years old made up 82%, students 20 – 23 years old made up 15%, and students over 23 years old made up the remaining 3%. Students taking part in this study had a wide level of previous mechanical, electrical, and computer systems experience. However, most did not consider programming skills as a primary goal in their education.

Measures

We measured students' motivational orientation using a pre- vs. post-test survey design. The instrument used was Pintrich and colleague's (1991) MSLQ and originated from the work of the National Center for Research to Improve Post-Secondary Teaching and Learning. It was validated and generalized across gender, race, and educational levels (Pintrich, et al., 1993), and has a substantial evidence base in the literature (Duncan & McKeachie, 2005). This instrument takes a meta-cognitive perspective of student motivation and learning. Specifically, it is predicated on the motivational constructs of *value choices*, *expectancy beliefs*, and *self-regulation*. As endorsed by the MSLQ manual

(Pintrich & Others, 1991), we used all 14 questions of the *value* (Intrinsic Goal Orientation (IGO), Extrinsic Goal Orientation (EGO), an Task Value (TV)) and all 17 questions from the *expectancy* (Control of Learning Beliefs (CLB), Self-Efficacy (SE), and Test Anxiety (TA)) subscales of motivational orientation (Table 3.2). However, the five questions from the TA item were not used in our analysis, as the course did not include traditional tests or exams. Responses for each were ordinal Likert Scale scores, ranging from 1 (“*not at all true of me”*) to 7 (“*very true of me”*). Item scores were calculated as the average of the responses to the corresponding questions. Each of the subscales were then calculated as the average of the corresponding items. These measures of motivation formed the multivariate dependent variable of motivational orientation.

Table 3.2
MSLQ sub-scale item questions used to measure students’ motivational orientation.

Subscale	Item	Questions
Value Components		
	Intrinsic Goal Orientation (IGO)	1, 16, 22, 24
	Extrinsic Goal Orientation (EGO)	7, 11, 13, 30
	Task Value (TV)	4, 10, 17, 23, 26, 27
Expectancy Components		
	Control of Learning Beliefs (CLB)	2, 9, 18, 25
	Self-Efficacy for Learning and Performance (SE)	5, 6, 12, 15, 20, 21, 29, 31
	Test Anxiety (TA)	3, 8, 14, 19, 28

Academic success was measured using final course grades, final project scores, and quiz scores. Values ranged from 0.00 to 1.00. The final course grades were assessed using a weighted combination of ten quizzes (10%), 15 in-class activities (15%), 12 essay questions (25%), one mid-term project (30%), and one final project (20%), all of which focused on applying a systematic, data-driven methodology for solving technical problems. Scores for the activities, essay questions, mid-term project, and the final project were evaluated by the course instructor and teaching assistants using the same rubrics for the control and treatment groups. All students were provided these rubrics before the completion of each assignment. Quiz scores were calculated as an average across five programming-centric quizzes. Grading of these quizzes were assessed using close-ended answer keys. This measure was used to answer our first and third research question.

In concert with the motivation scale items on our post-test survey, we included a multinomial response question that asked whether the mechatronic project motivated students. As part of this question, students were first presented with Meece, Clark, and Pintrich and Schunk's definitions of motivation (see Motivation Theory subsection above). Students were then asked to answer "Yes", "No", or "Neither". These responses were formed a separate, signal item measure of student motivation.

Data Collection

Pre- and post- surveys were collected during the spring (treatment) and fall (control) semesters of 2016. All surveys were administered through Qualtrics (Provo, UT), with the pre-survey collection occurring during week eight of the semester, and the post-survey collection occurring during week 16. This pre- vs. post- design allowed for *within* group comparisons, while the control vs. treatment design enabled *between* group analyses. Incentives, capped at 1% of the students' course grade, were awarded to participants who completed both a pre- and post-surveys. The pre- responses were linked to post- responses via the unique last five digits of students' identification numbers. Once this data link was made, and before the results were analyzed, all identifying information was removed from our data set. Additionally, all students received an informed consent allowing them to "agree" or "not agree" to participate in the surveys. No students under 18 years of age, or who responded, "not agree", were included in the dataset. This collection methodology was approved by our institution’s Institutional Review Board (IRB) as an exempt study under the human subject protections regulation, 45 CFR 46.101(b).

Data Analysis

All data analyses were performed using R version 3.3.3 (R Foundation for Statistical Computing, Vienna, Austria) and RStudio (RStudio, Inc., Boston, MA). Any R packages that were used, beyond those available in base R, are denoted below. All quantitative variables met the assumptions of quasi-random sampling and independent observations. While our sample sizes were unequal (control $n = 23$; treatment $n= 63$), this did not negatively impact the homogeneity of variance, therefore satisfying this model assumption (Skibba, n.d.).

Decisions of statistical significance for our two-tailed hypothesis tests were based on a Bonferroni adjustment, as shown by Equation 1,

$$\alpha = \frac{0.05}{n_{tests}} \tag{1}$$

where n_{tests} is the number of statistical test performed per research question. While the use of multivariate analyses (e.g., MANOVA) is often used in this scenario, repeated univariate analyses (e.g., ANOVA), with adjustments to guard against inflation of evidence, are an accepted statistical alternative that enable a simpler, more straight forward interpretation of the results (Pallant, 2005).

To answer the question of how students’ motivational orientation and academic success was different following a mechatronic experience, we calculated descriptive statistics with the psych package (Revelle, 2017) and one-way between-group Analysis of Covariance (ANCOVA) tests, using Type I Sums of Squares. Analyzing the effects on the multivariate dependent variable of motivational orientation, we used the categorical predictor variable of group assignment (treatment or control). To control for pre-existing differences between groups, we included the covariates of pre-survey motivational orientation, previous semester GPA, and composite ACT scores. Examining the effects on the multivariate dependent variable of academic success, we used the same predictor and covariate variables, less pre-survey motivational orientation scores. The assumptions of normality, linearity, homogeneity of variance, homogeneity of regression slopes, and reliability of covariate usage were satisfied once missing values of students' composite ACT scores were imputed using the Multivariate Imputation by Chained Equations (MICE) package (van Buuren & Groothuis-Oudshoorn, 2011) and post-survey MSLQ results were square transformed for normality. Where statistically significant differences were found, Cohen's *d* (1992) was used to calculate the size of effect for ANOVA tests using the effsize package (Torchiano, 2017) and interpreted per Cohen's proposed small = 0.20, medium = 0.50, and large = 0.80 (1992).

Our second research question asked students to select whether they had been motivated or not by the experience. To answer this, we analyzed the difference in the proportion ($\hat{\pi}$) of students who reported "Yes" vs. those who reported "No" or "Neither" (combined as "Not_Yes") using a Fisher's Exact test (Fisher, 1922). This consolidation was used due to the small sample size of aggregate responses for "No" (5, 6%) and "Neither" (6, 7%). We reported Cohen's *h* as a measure of the effect size (strength of association) of our odds ratio test, as appropriate (i.e., statistically significant results). Again, we interpreted values per Cohen's suggested small = 0.20, medium = 0.50, and large = 0.80 (1992).

The third research question examined the relationship between students' motivational orientation and the level of academic success, for both control and treatment groups. To answer this, partial Pearson's correlations (*r*) were used to explore the relationship between academic success (final project scores) and their motivational orientation (post-survey levels minus pre-survey levels), while controlling for students' previous semester GPA. We found no violations of the assumptions of normality, linearity, and homoscedasticity after missing values of students' previous semester GPA scores (e.g., first semester freshman) were imputed using the MICE package (van Buuren & Groothuis-Oudshoorn, 2011), post-survey MSLQ results were square transformed for normality, and course grades were Box-Cox transformed using the car package (Fox & Weisberg, 2011). We also used paired-sample *t*-tests to test whether there was a significant difference between the correlation coefficients of the control group compared to the treatment group (i.e., r_1 vs. r_2) for each subscale and item of motivational orientation. We used the cocor package (Diedenhofen & Musch, 2015) for this and reported *z* statistic for these tests, per Fisher (1925). Effect sizes for difference in group correlation coefficients were reported using Cohen's q (i.e., small = 0.10, medium = 0.30, and large = 0.50) (1992).

Results

Levels of motivation and academic success

The first objective of this chapter was to examine whether there was a difference in student motivational orientation in the treatment vs. control group. Analyzing the influence of outliers in our dataset, we found no significant impact. This was based on a paired-sample *t*-test of post-survey motivational orientation means (*M*=5.45*, SD*=0.16) vs. 5% trimmed means (*M*=5.48*, SD*=0.16, *t*(8)= -0.2849, *p*=0.7830) and academic success means (*M*=0.86*, SD*=0.04) vs. 5% trimmed means (*M*=0.87*, SD*=0.04, *t*(4)= -0.3308, *p*=0.7575). Turning to descriptive statistics of unadjusted motivational orientation scores (Table 3.3), we found that the means for all subscales and items (except EGO) were higher in the treatment vs. control group. However, when we controlled for differences in pre-experience motivational orientation (i.e., pre-survey MSLQ scores) and prior academic achievement (i.e., GPAs and ACTs), we found no statistical evidence that these mean scores were higher in the mechatronic experience [*F*(6,77)=0.03, *p*=0.8630]. This was based on a one-way between-groups ANCOVA ($\alpha = 0.05$). Further testing the *value* and *expectancy* subscales separately, we again found no statistical difference in the mean scores for either *value* [*F*(6,77)=0.13, *p*=0.7224] or *expectancy* [*F*(6,77)=0.38, *p*=0.5408]. Moreover, no evidence was found that the mean scores of the individual items of IGO, EGO, TV, CLB or SE where higher following the mechatronic experience [all tests: *F*(6,77)≤2.66, *p*≥0.1069]. In short, we were not able to claim that the gains in mean motivational orientation in Table 3.3 were due to the mechatronic experience. The higher mean scores of motivational orientation in our treatment group could be due to confounding variables or chance. We would need a combined sample size of roughly 800 (*expectancy*) and 2,300 (*value*), to statistically claim a difference (with an 80% probability of being correct). To our knowledge, no previous literature has indicated the need for sample sizes of these magnitudes.

Next, we examined differences in academic success. While the means of course grades and project scores were higher in the treatment vs. the control group, the means of quiz scores were lower (Table 3.3). Controlling for GPA and ACT scores using a one-way between-groups ANCOVA ($\alpha = 0.0167$ for three related tests), we found strong statistical evidence that mean course grades were higher in the mechatronic experience group [$F(5,78)=7.76$, $p=0.0067$, $1\text{-}\beta=0.81$]. This resulted in a medium effect size ($d=0.70$, $d_{95\%CI}=0.20$ to 1.20). Statistical evidence was also found that project scores were higher in the mechatronic experience group [$F(5,78)=6.51$, $p=0.0127$, $1\text{-}\beta=0.50$]. This resulted in a small effect size ($d=0.48$, $d_{95\%CI}=0.00$ to 0.98). In contrast, the mechatronic experience did not exhibit statistical evidence of an effect on quiz scores [$F(5,78)=0.25$, $p>0.6150$]. There were no appreciable interaction effects between academic success and GPAs or ACTs either [all tests: $F(5,78)<2.32$, $p>0.1315$].

Table 3.3
Unadjusted descriptive statistics of motivational orientation and academic success.

	Control (n= 23)					Treatment (n= 61)				
Dependent Variable	M	SD	M_{trim}	Min	Max	M	SD	M_{trim}	Min	Max
Value/Expectancy	5.35	0.75	5.38	3.75	6.70	5.49	0.75	5.53	3.82	7.00
Value	5.37	0.68	5.39	4.00	6.58	5.46	0.83	5.48	3.58	7.00
Expectancy	5.33	0.89	5.38	3.50	6.81	5.53	0.75	5.57	3.69	7.00
IGO	5.20	0.80	5.17	4.00	6.50	5.40	0.91	5.42	3.50	7.00
EGO	5.66	0.66	5.67	4.25	7.00	5.46	0.98	5.49	2.75	7.00
TV	5.26	1.03	5.30	3.00	6.83	5.51	1.16	5.62	1.50	7.00
CLB	5.14	1.00	5.21	2.75	6.75	5.31	0.92	5.35	3.00	7.00
SE	5.52	0.82	5.57	3.75	6.88	5.74	0.77	5.76	3.88	7.00
Course Grade	0.87	0.07	0.88	0.64	0.97	0.90	0.08	0.91	0.56	0.99
Project Score	0.81	0.18	0.83	0.40	1.00	0.89	0.08	0.91	0.49	1.00
Quiz Score	0.83	0.08	0.84	0.67	0.98	0.82	0.10	0.83	0.55	0.94

Proportion of motivated students

Looking at Table 3.4, we see that 55 (90%) of the treatment group students reported that the mechatronic experience was motivating (per Meece, Clark, and Pintrich and Schunk's definitions). In comparison, 18 (78%) of the control group students felt that the non-mechatronic experience motivated them (per the same definitions of motivation). To test whether there was statistical evidence that these proportions were different, we used a Fisher's Exact test. We found no evidence that the proportion of motivated students in the treatment group [$\hat{\pi}=0.90$] was different than in the control group [$\hat{\pi}_1 - \hat{\pi}_2=0.12$, $p=0.1634$, $OR=2.51$, $h=0.33$]. To be able to state statistical evidence of a difference (based on our data and 80% power), we would have needed a combined sample size of close to 300. To our knowledge, recommendations of this sample size have not previously been published.

Table 3.4
2 x 2 contingency table for whether students were motivated by the experience.

	Response		
Group	Not Motivated	Motivated	Total
Control	5	18	23
Treatment	6	55	61
Total	11	73	84

Relationship between motivation and academic success

To understand the relationship between each subscale and item of motivational orientation, as well as final project scores, we calculated Pearson's partial correlation coefficients (r), while adjusting for students' previous semester GPA (Table 3.5). In the control group, every value of r was not significantly different from zero, except for the *value/expectancy* vs. final project score [$r=0.47$, $p=0.0291$] relationship. However, more interesting than the control's *value/expectancy* result, was what we found for the treatment group. There was no significant relationship between students' final project scores and the value they placed on the final project or the belief(s) they held in their ability to effectively complete it. This result was true for each of the items within *value* and *expectancy* as well [all tests: $p>\alpha$]. Using paired-sample t-tests, we statistically confirmed there to be no difference between our control and treatment group's *r* values [all tests: $r_1 - r_2 \leq 0.46, p > 0.0417$]. This was true for all the motivational orientation subscales and items (Table 3.6). Even so, it is interesting to point out that, while not statistically significant ($\alpha = 0.0063$ for repeated tests), the relationship between SE and final project scores was below the common significance level for single hypothesis *a priori* research questions [control *r*=0.54*,* treatment *r*=0.08*, p*=0.0417]. While we cannot claim a significant difference, there appears to be a meaningful relationship between self-efficacy and academic success (when adjusting for GPAs).

Table 3.5
Within group Pearson's partial correlations of motivational orientation and final project scores, while adjusting for pervious semester GPA.

	Control			Treatment			
	r	Statistic	*p-value*	*r*	Statistic	*p-value*	α
Value/Expectancy	0.47	2.35	0.0291	0.07	0.52	0.6048	0.0500
Value	0.13	0.58	0.5679	0.08	0.64	0.5226	0.0167
Expectancy	0.27	1.26	0.2207	-0.01	-0.07	0.9444	0.0167
IGO	0.07	0.30	0.7702	0.14	1.07	0.2871	0.0063
EGO	0.07	0.33	0.7421	-0.02	-0.12	0.9016	0.0063
TV	-0.12	-0.55	0.5901	-0.07	-0.50	0.6169	0.0063
CLB	0.25	1.18	0.2531	-0.10	-0.79	0.4315	0.0063
SE	0.54	2.90	0.0089	0.08	0.62	0.5351	0.0063

Note: $n = 84$; H_0: $r = 0.00$, bolded *p-values* indicate values below the α of the corresponding hypothesis test.

Table 3.6
Between group t-tests of difference in Pearson's partial correlations of motivational orientation and final project scores, while adjusting for pervious semester GPA.

	r_1-r_2	*z-value*	*p-value*	α
Value/Expectancy	0.40	1.68	0.0929	0.0500
Value	0.04	0.17	0.8619	0.0167
Expectancy	0.28	1.11	0.2663	0.0167
IGO	-0.07	-0.29	0.7741	0.0063
EGO	0.09	0.35	0.7261	0.0063
TV	-0.06	-0.22	0.8286	0.0063
CLB	0.36	1.40	0.1604	0.0063
SE	0.46	2.04	0.0417	0.0063

Note: $n = 84$; H_0: $r_1 \neq r_2$.

Discussion

Based on the results above, we revised the theoretical framework in Figure 3.1 to what is illustrated in Figure 3.2. This is presented to graphically show the general relationships we found between mechatronic experiences, motivational orientation (i.e., student motivation), and academic success. A detailed discussion of these relationships is given below.

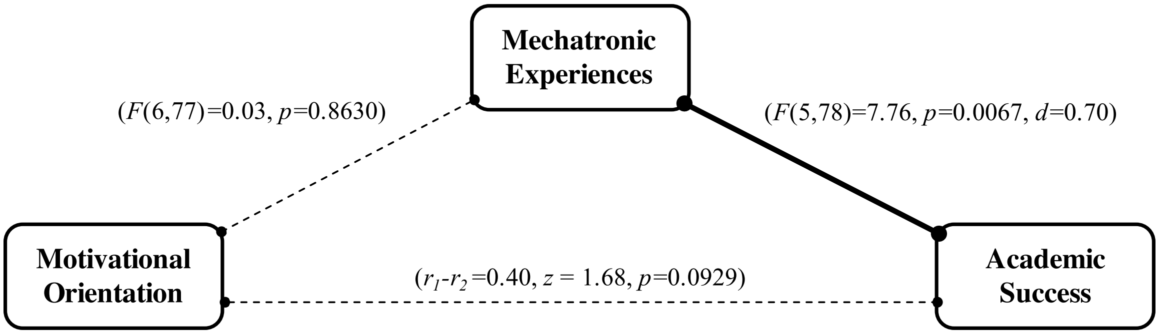

Figure 3.2
Revised framework of the relationship between mechatronic experiences, motivational orientation (i.e., student motivation) and academic success, based on research findings. Solid lines indicated statistically significant relationships, while dashed lines indicated statistically insignificant relationships.

Levels of motivation and academic success

The first part of research question one asked if there was a difference in motivational orientation in the treatment vs. control group. We did not observe different levels of motivational orientation in the treatment group (top left dashed line of Figure 3.2). While this is in contrast to current literature that has stated improvements to student motivation following mechatronic experiences (Castles et al., 2010; Durfee, 2003; McLurkin et al., 2013; Nedic et al., 2010; Verner & Ahlgren, 2004), we posit that the research designs undergirding these findings appeared to have been predicated on single item questionnaires that were most often administered once. They did not administer pre/post surveys or compare control vs. treatment groups. Therefore, we argue for two alternative explanations: 1) previously observed effects of mechatronic experiences on the *value* and *expectancy* dimensions may not be as drastic as thought, and 2) previously observed impacts on *value* and *expectancy* may not have been due to mechatronic experiences. Looking at more historic research, it is well documented that motivation has a tendency to decrease over time (Zusho, Pintrich, & Coppola, 2003). Additionally, interest (i.e., *intrinsic goal orientation*) has been found to peak during the middle of a project, and wane towards the end (Rotgans & Schmidt, 2011). While these do not speak directly to the statistical similarity of mean scores observed in our study, they do indicate the dynamic nature of motivation that could be confounding a positive change in motivational orientation. Does motivation change at similar rates or degrees for mechatronic vs. non-mechatronic experiences? Are peaks in motivation the same, or do they occur at similar points in an experience? Future work is required to answer these questions. However, it is important to highlight that we did not observe a negative impact on motivational orientation in the mechatronic experience group. This would indicate that implementing this type of rigorous, multidisciplinary experience may not demotivate students. This alone could call for the use by engineering and technology educators, who are looking for an integrative, applied experience that spans technical domains.

Part two of research question one asked if there was a difference in academic success in the treatment vs. control group. We found significant differences for course grades and project scores (solid line of Figure 3.2). Students who engaged in the mechatronic experience averaged three percentage points higher on course grades and eight percentage points higher on final project scores. This translated to an average course grade of A- in the treatment group vs. B+ in the control group, and an average final project score of a B+ in the treatment group vs. a B- in the control group. From a student's perspective, this is a practically significant difference, especially those applying for scholarships. This aligns with the concept that a medium effect is "likely to be visible to the naked eye of a careful observer" (Cohen, 1992, p. 156).While this does not prove causality (assignment to experimental groups was not random, thus no directional arrow in Figure 3.2), it does reveal an association between mechatronic experiences and improved academic success in open-ended problem-solving projects and courses. This is not surprising, as these experiences require students to integrate divergent technical domains towards an effective solution. Harnessing this skill is central to authentic problem solving. This aligns with various studies that have linked mechatronic experiences with motivation, or motivation with engagement, or engagement with academic success (as indicated by Figure 3.1). More significantly, our findings make a strong connection between each end, thus supporting the link between the parts, as indicated by Duncan and McKeachie (2005). However, when considering quiz scores, academic success was not different for the treatment vs. control group. This would indicate that students' knowledge of content (specifically programming syntax) was not affected by the mechatronic experience. This is juxtaposed to research that found students' knowledge of content (specifically electronic sensors) to be higher following a mechatronic experience compared to the same students' levels after a baseline experience (McLurkin et al., 2013). This study did not compare scores against a separate control group, possibly leading to differing results. Another explanation could be that mechatronic experiences impact knowledge retention differently for different content domains. As a note of comparison, the same grading rubrics and schemes were used to measure course grades, project scores, and quiz scores for the control and treatment groups. This was done to mitigate confounding variability when measuring these variables.

As an interesting side note, we did find a slight interaction (*p-value*=0.0332) between GPA and group assignment, when considering the dependent variable TV. To be clear, we cannot claim that this indicated statistical evidence of a difference between the control vs. treatment groups (*p-value* > α). However, what we can say is that there could be slight differences between control vs. treatment levels of TV, when accounting for GPA. This could indicate that higher achieving students find less value in the mechatronic experience vs. lower achieving students (*vice versa* in the control group). This parallels the inverse relationship found between a student's prior level of knowledge and the level of effort they exert towards a goal (Clark, 1998). Could it be that the value placed on a mechatronic experience is mediated by their previous level of academic achievement (i.e., higher achieving students are less motivated by mechatronic experiences)? Again, future research is needed to understand these relationships.

Proportion of motivated students

Our second research question looked at whether there was a difference in the proportion of students who reported being motivated in the treatment vs. control group. We found no difference (again, top left dashed line in Figure 3.2). This corroborates results found for our first research question. Just as we did not find a difference in reported levels of motivational orientation, we did not find a difference in the proportion of students that were motivated. The hands-on, multi-disciplinary, technical nature of mechatronics had no significant impact on motivation. Therefore, wise consideration is called for when deciding to implement these experiences, especially if the purpose is to impact student motivation, as defined by Meece, Clark, and Pintrich and Schunk (see Motivation subsection above).

Relationship between motivation and academic success

Looking at research question three, we asked if there was a relationship between motivational orientation and academic success. We found almost no correlation (bottom dashed line in Figure 3.2). The only exception was a positive relationship between *value/expectancy* and final project scores in the control group. This indicated that, in the control group, students who reported higher levels of motivational orientation (e.g., combined IGO, EGO, TV, CLB, and SE) earned higher final project scores. This is not surprising, as these subscales are considered adaptive motivational beliefs and have been positively linked to academic success (Zusho et al., 2003) However, this positive relationship did not hold true for the individual subscale items or in the treatment group. Moreover, we found no difference in the relationship between students' *value choices* or *expectancy beliefs* and final project scores when comparing the control vs. treatment groups. This would indicate that the mechatronic experience had no impact on the relationship between students' level of motivation and academic success. While much literature has found a positive relationship between these variables (e.g., the more a student is motivated towards an academic goal the higher the level of achievement they attain for that goal) (Credé & Phillips, 2011), we concluded that the mechatronic experience had no effect, positive or negative, on the strength of relationship between motivational orientation and academic success. This was not surprising, as this again confirms results found from our first two research questions.

Limitations

While we strove for rigor in our study, limitations still exist. First, our measures of motivation were based on students self-reported responses. While one can argue that the used of this type of data is limiting, there is a well-established record of literature that has used the same instrument and methods to measure motivation (Duncan & McKeachie, 2005). Therefore, we did not feel it was unreasonable to inform our conclusions based on self-reported responses.

Next, we did not consider the limitations due to our non-random quasi-experimental design unrealistic. This is a common scenario found in educational research (Trochim & Donnelly, 2001), and only encumbers how broadly one can generalize our findings.

Another limitation was the non-equivalent sample size of the control and treatment groups. While this is often considered an issue in ANOVA/ANCOVA, it is really only an issue if and when it adversely affects the assumption of homogeneity of variance (Skibba, n.d.). As we did not find our data to violate this assumption, we felt comfortable with this analysis model. However, this did add to our inability to find a statistically significant difference in motivational orientation. This was beyond our control, as sample size needs have not been previously published.

Finally, variability from the instructor was not included in our analysis. The same instructor taught the control and treatment groups. While this consistency was used to mitigate confounding variability of instructor differences, it did not account for the instructor's engagement level. The instructor was highly motivated to engage with and motivate the students, regardless of the content being taught (e.g., mechatronics or non-mechatronics). While we felt this removed variability of instructor differences, instructor engagement may still have overshadowed the effect of the mechatronic experience on motivational orientation results.

Conclusion

Recommendations

Statistically significant differences were not found in the levels of motivation orientation between our control vs. treatment group. While we did observe higher mean scores in the treatment group, our sample sizes were not large enough to produce statistical significance. As noted, no previous studies have been published that indicate the required sample sizes or effect sizes for this phenomenon. We recommend more research that examines the effect size of mechatronic experiences on motivational orientation. This will help to define what sample sizes are needed based on expected effects.

Furthermore, research has indicated motivation to be dynamic throughout a project. It can peak during the middle and drop at the end. This raises several questions: Does motivation change at similar rates or degrees for mechatronic vs. non-mechatronic experiences? Are peaks in motivation the same, or do they occur at similar points in an experience? Therefore, we also recommend future research that examines the profile shape of motivational orientation over the course of a mechatronic project, not just at a pre- and post- interval.

We did find a slight interaction between GPA and group assignment [$F(6,77)= 4.70, p=0.0332$], when considering Task Value. While it was not statistically significant, based on an $\alpha = 0.0063$ for repeated tests, this could indicate that higher achieving students find less value in the mechatronic experience vs. lower achieving students (*vice versa* in the control group). Could it be that the value placed on a mechatronic experience is mediated by their previous level of academic achievement (i.e., higher achieving students are less motivated by mechatronic experiences)? Again, future research is recommended to understand this more fully.

Even though we found statistically significant differences in academic success, we only accounted for covariates of GPA and ACT scores. We would recommend also considering variables such as students' academic major, age, class level, previous technical experience, ethnicity, and/or gender identification.

Finally, we would recommend that future research be conducted that examines how instructor variability (e.g., engagement in teaching, motivation toward content, or instructional quality) affects students' motivational orientation and academic success. This was outside the scope of our study. However, literature has empirically found that students with enthusiastic instructors had higher levels of student motivation and academic success (Kunter et al., 2013). Specifically, this variability of instructor quality could be included as a covariate in an ANCOVA model. This could especially improve the model's ability to distinguish between differences in motivational orientation between the control and treatment groups.

Summary

In this chapter, we presented results that empirically quantify the differences in undergraduate students' motivational orientation and academic success for a mechatronic experience vs. a non-mechatronic experience. Specifically, we found motivational orientation was not negatively impacted. However, academic success was significantly higher in the treatment group. When looking at the association between motivational orientation and academic success, we found no relationship. Synthesizing these findings, we are encouraged. The more rigorous mechatronic experience did not lower students' motivational orientation. Even more encouraging, project scores and final course grades were higher in for the mechatronic experience group. We hope these findings will strengthen the empirical evidence of differences associated with these experiences.

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CHAPTER 4. INNOVATIVE APPLICATION OF INCREMENTAL COST ANALYSIS IN ENGINEERING EDUCATION

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Abstract

Many experiences in engineering education boast positive gains to students' learning and achievement. However, current literature is less clear on the economic costs associated with these efforts, or methods for performing said analyses. To address this gap, we proposed a structured approach to analyzing the incremental costs associated with an experience in engineering education. This method was modelled after those found in medicine and early childhood education. We illustrated the innovative methodology using marginal (above baseline) time and cost ingredients that were collected during the *development*, *pilot*, and *steady-state* phases of a mechatronic experience in a first-year undergraduate engineering technology course. Specifically, our method included descriptive analysis, Pareto analysis, and cost per capacity estimate analysis, the latter of which has received limited discussion in current cost analysis literature. The purpose of our illustrated explanation was to provide a clear method for incremental cost analysis of experiences in engineering education. We found that the *development, pilot,* and *steady-state* phases cost just over \$17.1k (~\$12.4k for personnel and ~\$4.7k for equipment), base on 2015 US\$ and an enrollment capacity of 121 students. Cost vs. capacity scaled at a factor of -0.64 ($y = 3{,}121x^{-0.64}$, $R^2 = 0.99$), which was within the 95% interval for personnel and capital commonly observed in the chemical processing industry. Based on a four-year operational life and a range of 20 – 400 students per year, we estimated per seat total costs to range from roughly \$70 – \$470, with our mechatronic experience averaging just under \$150 per seat. Notably, the *development* phase cost, as well as the robot chassis and microcontroller capital cost were the primary cost terms.

Keywords: incremental cost analysis; cost-effectiveness analysis; cost ingredients

Introduction

In a recent systematic review by our group (Haughery & Raman, 2016a), we found that current literature surrounding the use of mechatronic experiences in technology and engineering education primarily focus on the effects on student learning, motivation, and engagement, with limited discussion given to the incremental costs incurred. While some studies proposed educational frameworks for these interventions (Wang, Yu, Xie, Zhang, & Jiang, 2013) and others analyzed the economics of these systems apart from an educational application (Wittbrodt et al., 2013), none focused specifically on the incremental costs incurred by these. In this research, we defined a mechatronic experience as a project or activity that requires students to design and/or develop a machine that performed a defined function or task (Verner & Ahlgren, 2004). This inherently requires the integration of mechanical and electrical hardware systems with computer software systems. These experiences are a tangible example of project-based learning (PjBL) and problem-based learning (PbBL), which both garner much acceptance in science, technology, engineering, and mathematics (STEM) education. Matthew and Hughes (1994, p. 239) advocate that these pedagogies and related experiences enable “students to perform at the cognitive levels which academics intuitively wish them to.” However, Yadav *et al.* (2011) call for further research to better understand how generalizable the effects of PjBL, PbBL, and related experiences are to a broad range of educational scenarios. Likewise, it is increasingly important to quantify the monetary impact of these pedagogies, as educational funding has dropped nearly 30% compared to fiscal year 2000 funding (American Academy of Arts & Sciences, 2015). While there is a well-established literature for cost analysis of general education and health interventions (Drummond, Sculpher, Claxton, Stoddart, & Torrance, 2015; Levin & McEwan, 2001), we are unaware of any literature that has focused on the incremental costs of PjBL or PbBL experiences in engineering/technology education.

To find the first substantial publication on cost analyses in education, one must start with Levin’s (1975) *Cost-Effectiveness Analysis in Evaluation Research* and Rothenberg’s (1975) *Cost-Benefit Analysis: A Methodological Exposition*, both printed in the *Handbook of Evaluation Research*. Levin followed this initial publication with a book titled *Cost-Effectiveness: A Primer* (1983), in which he outlined three distinct approaches to costing (e.g., cost-benefit analysis, cost-effectiveness analysis, and cost-utility analysis). Six years later, Barnett and Escobar (1989) published a very succinct review of select studies using either *cost-benefit analysis* (CBA) or *cost-effectiveness analysis* (CEA) for elementary education interventions. In all these examples, they stressed the need for longitudinal studies that capture the effects, costs, and benefits to the target population *and* society. Twelve years later, Levin and McEwan published a revise edition under the title *Cost-Effectiveness Analysis: Methods and Applications* (2001) in which they added a forth approach: cost-feasibility analysis. The first three approaches are intended to provide decision makers (i.e., administration, policy makers, or institutional leaders) with a unit cost per unit benefit, unit cost per unit effect, or unit cost per unit utility, while the forth is intended to allow them to quickly evaluate competing alternatives against a budget. More recently, Scharff, McDowell, and Medeiros (2009) and van der Velde *et al.*, (2011) have presented similar methods for evaluating the cost-effectiveness and/or cost-benefits of educational interventions in food science and medical education, respectively. McEwan (McEwan, 2012) provides an in-depth framework for conducting CEA in education and medicine, among other analysis approaches. He defines CEA as the incremental cost ($) per unit of incremental effect, allowing for an incremental cost per incremental unit effect ratio (CER) or incremental effect per incremental unit cost ratio (ECR) to be calculated. From this ratio, a clear relationship between costs and effects of an experience can be realized (i.e., how large of an increase in test scores was realized per x dollars spent, or how many dollars will need to be spent to increase test scores by y points). Levin and Belfield (2015) indicated CEA as the most versatile and direct approach to evaluating the economics of an experience.

Focusing on incremental costs, Levin (1983) and Levin and McEwan (2001) give specific "ingredients" that can be quantified and compared against either incremental effect, benefit, or utility. These costs function as opportunity costs and offer a direct mechanism for quantifying the economics of an experience (Levin & Belfield, 2015). These inputs include: *personnel* (i.e., full-time, part-time, consultant, volunteer, etc.

human resources), *facilities* (i.e., classrooms, offices, storage space, land, etc.), *equipment and materials* (i.e., furniture, scientific apparatus, instructional equipment, experience material, computer equipment, commercial tests, etc.), *client inputs* (i.e., books, uniforms, transportation, etc. required of clients), and *other inputs* (i.e., all other miscellaneous costs that do not readily fit into other ingredient categories). These ingredients are then valued using either market prices (if their market value is known) or shadow prices (if their market value is unknown) and evaluated over a single or multi-year span. When considering experiences that stretch across multiple years, it is important to account for inflation and the time value of money. Levin and McEwan (2001) specify that for situations where monetary expenditures are made across multiple years, future and past “nominal” costs should be adjusted for inflation to a predefined present “real” cost (i.e., the market value of a predefined product or service in year one will change in value in year two, due to inflation). For situations where expenses are made in future years, Levin and McEwan (2001) stipulate that these costs should be discounted to account for the time value of money (i.e., the opportunity cost of spending a dollar now is higher than if that dollar is spent in the future). With these approaches, longitudinal studies that include a broad scope of cost elements can be effectually evaluated. However, current literature offers limited discussion of *ex ante* situations that forecast costs into the future or across different experience sizes.

A defined method for analyzing incremental costs and scalability of an experience are not novel. However, the use of this analysis in engineering education, and more specifically the use of *ex ante* analysis, does appear to be innovative. Therefore, we proposed a “preliminary best practice” method that focused on incremental cost analysis of experiences in engineering education. This method includes descriptive and Pareto *ex post* analysis, as well as cost per capacity *ex ante* estimate analysis. In so doing, we sought to achieve the research objective of quantifying the *ex post* costs and *ex ante* scalability of implementing a mechatronic experience. To meet this objective, we asked the following research questions:

- What incremental costs are associated with implementing a mechatronic experience?
- How do these costs scale with class size?

Materials and Methods

To help clarify the application of our method, we present example data from a study focusing on the costs and scalability of a mechatronic experience in a first-year undergraduate engineering technology course offered at a large Midwestern university in the United States of America (Haughery & Raman, 2016b). Our data represent the marginal *personnel* and *equipment/material* (capital) costs incurred by the experience that were above and beyond the *status quo* educational costs, as defined by Levin and McEwan's (Levin & McEwan, 2001) costs "ingredient" approach. These data were collected over a 13-month period during the *development* (March – October 2015), *pilot* (October 2015 – January 2016), and *steady-state* (February – May 2016) phases of our experience, per the Institute of Education Science's *Common Guidelines for Educational Research and Development* (Institute of Education Sciences, 2013) protocol.

Personnel Ingredient

Personnel expenditures were comprised of instructor and support staff – teaching assistants (TAs), lab technical staff, and administrative support staff – time and costs. One instructor developed the mechatronic experience. During the *pilot* and *steady-state* phases, data were collected from this single instructor, who also was teaching four course sections (35 – 48 seats per section) over a two-semester period with one additional TA per section. Personnel cost (P_k) in US$ accrued during the *development*, *pilot*, and *steady-state* phases of the study were calculated to the nearest dollar using Equation 1,

$$P_k = \sum_{k=1}^{3} \left[T_{ijk} \left(\frac{S_i}{Y_i} \right) 1.51 \right] \tag{1}$$

where T_{ijk} is the time (hours) expended by the i^{th} personnel category, on the j^{th} task, during the k^{th} phase, with k taking on the values of 1 = *development*, 2 = *pilot*, and 3 = *steady-state*; S_i is the median base salary (US$) per i^{th} personnel category, and Y_i is the time (hours) worked per year per i^{th} personnel category. The 1.51 is an indirect cost multiplier (Iowa State University, 2016). Support staff yearly times were estimated at 2,080 hours (i.e., 52 weeks per year at 40 hours per week) and instructor yearly time was estimated at 2,196 hours (i.e., 9 months per year at 4 weeks per month at 61 hours per week). The 61 hours per week for instructor time was based on the preliminary results from the Time Allocation Workload Study (Ziker, 2014), and a common nine month tenure-track appointment period.

Table 4.1
Mechatronic equipment bill of materials, in US$.

Qty	Part Number	Description	Manufacturer	Reference Link	Unit	Total	Sub*
26	3124	ZUMO Robot (Assembled w/ Motors)	Pololu	http://goo.gl/Yuqdwm	$80	$2,080	RP
50	DEV-11021	Arduino UNO Rev3 Microcontroller	Arduino	http://goo.gl/BN6pCh	$25	$1,250	RP
50	CAB-00512	USB Programming Cable, 6'	N/A	http://goo.gl/uUyfw2	$3	$150	SE
7	N/A	AA Recharge Batt., 2100mAh, 16 pc	Rayovac	http://goo.gl/57EmB5	$30	$210	SE
13	N/A	8xAA Battery Charger, NiMH	Rayovac	http://goo.gl/j9o2RD	$10	$130	SE
1	N/A	12" Extension Cord	Topzone	http://goo.gl/n9fgRF	$9	$9	SE
1	50281	3-Outlet Tap	GE	http://goo.gl/BCELsw	$6	$6	SE
1	N/A	6-Outlest Surge Protector, 2pk	AmazonBasics	http://goo.gl/DumuKJ	$12	$12	SE
1	900803	Foam Board, 10pk	Elmer's	http://goo.gl/gmIBvV	$55	$55	SE
9	N/A	30" x 40" Project Course, B/W	Campus Printing	N/A	$5	$47	SE
1	NW0600-0402N-M	Rolling Storage Case	Lista	N/A	$787	$787	SE
					Total:	$4,736	

*RP = Robot Platform, SE = Support Equipment.

Capital Ingredient

The bill of material (BOM) used in our experience is illustrated in Table 4.1. These items were selected based on a review of relevant literature (Haughery & Raman, 2016a), instructor input, and professional experience. As with personnel time, the BOM only included items beyond the course's baseline capital equipment requirements and was divided into the subcategories of *robot platform* (RP) and *support equipment* (SE). The equipment list was developed for a maximum course section capacity of 50 seats, with one Arduino (Arduino, USA) microcontroller per seat, one ZUMO (Pololu, Las Vegas, NV) robot chassis per two seats, and the remaining ZUMO for instructor demonstration. This BOM equipment was shared across four course sections (121 total seats) during the *pilot* and *steady-state* phases of the study. The ZUMO came pre-assembled with two metal-geared motors, integrated motor drive circuits, three-axis accelerometer/compass, piezo-electric buzzer, status light emitting diodes (LEDs), a user pushbutton, and an infrared reflectance sensor array for high contrast sensing. The capital cost (C) in US$ of this BOM was calculated to the nearest dollar using Equation 2,

$$C = \sum_{i=1}^{n} (A_i) k_i \tag{2}$$

where A_i is the acquisition cost (2015 US$), including tax, per the i^{th} BOM item, k_i is the unit quantity per the i^{th} BOM item, and n is the total number of items.

Data Analysis

To facilitate preliminary *ex post* incremental costing, we presented a descriptive analysis of the per phase, position, and category times and costs (Table 4.2) of our mechatronic experience. From this we move to Pareto analysis (Juran & Riley, 1999) to identify the vital few (~20%) personnel tasks and capital items that contributed to a majority (~80%) of the overall time and cost of the mechatronic experience. Defining these cut points was accomplished by identifying the first drastic step-down between adjacent bars of the Pareto chart (West, 2008); in instances lacking a drastic step-down, a threshold at the 60% cumulative mark can denote items comprising the vital few (West, 2008). This analysis isolates the vital few tasks and items that should be tracked on even the most rudimentary cost analysis. We present these key tasks and items in the Results and Discussion section below.

Moving to an *ex ante* analysis, we estimated incremental per seat costs in US$ for personnel (P'), capital (C'), and total personnel and capital (T'). These estimates were done across a four-year deployment period for a range of seat capacities using Equation 3a, 3b, and 3c,

$$P' = \frac{\frac{P_1(1+r)^n}{n} + \frac{mP_3}{1}}{\alpha} \tag{3a}$$

$$C' = \frac{[C + (\alpha)R](1+r)^n}{\alpha} \tag{3b}$$

$$T' = P' + C' \tag{3c}$$

where (α) is the yearly seat capacity and takes values from 20 to 400, in increments of 10; *development* cost is amortized based on a simple future value using an August 2015 interest rate (*r*) of 0.11 (US Federal Reserve, 2015) with a deployment period (*n*) of four years; *steady-state* instructor and TA costs repeat every *m* course sections in discrete increments of 50 seats; capital and repair costs are amortized using a simple future value; and R is the repair cost multiplier per seat, calculated using Equation 4,

$$R = \frac{2(r_A)}{121} \tag{4}$$

where r_A is the repair cost of $19.95 that was accrued (US$) during the first year of deployment (*pilot* and *steady-state*) to 121 seats with a safety factor of two. This method of calculating a repair cost multiplier based on historical repair costs was assumed to be the best estimate of future repair costs (Edwards, 2015). No salvage value adjustments were made to the total cost at the end of the deployment period. Equations 3a – 3c then allowed us to quantify costs scaled with per year seat capacities (i.e., per year class size). To do this, we used a power function model, as illustrated by Equation 5,

$$y = k(x)^a \tag{5}$$

where *y* is the cost (US$), *k* is the constant of proportion of cost (US$), *x* is the capacity (i.e., per year number of seats), and *a* is the power factor describing the incremental scaling relationship between cost and capacity. This analysis was borrowed from the chemical processing industry, were power factor modeling has been used for well over a half century. We feel it is well suited to the field of engineering education, as it allows for straight forward per seat (or per course section) incremental cost analysis for an experience. When looking at historical data from the chemical process industry, personnel costs divided by capacity have been found to commonly scale at a factor of *a* =

-0.60 with 95% of observations ranging from $-1.00 \leq a < -0.40$, while equipment capital costs divided by capacity typically scale at a factor of $a = -0.40$ with 95% of observations ranging from $-0.70 \leq a < 0.10$ (Haldi & Whitcomb, 1967). We compared our results with these scaling factors and intervals, due to the lack of evidence available in the literature related to mechatronic experience costing.

Results and Discussion

Ex Post Descriptive: Phase, Position, and Category

Over the 13-month study period, the overall time and cost for *development*, *pilot*, and *steady-state* phases of the mechatronic experience were close to 280 hours and slightly over $12.4k, respectively (Table 4.2). Separating these totals by phase, *development* totaled 171 hours (61% of total) and $9,497 (77% of total), *pilot* phase totaled 58 hours (21% of total) and $1,574 (13% of total), and *steady-state* totaled 53 hours (19% of total) and $1,329 (11% of total). As expected, *development* time and cost were both greater than *pilot* or *steady-state* time and cost, with *development* times averaging nearly 3.0 and 6.5 times greater than either *pilot* or *steady-state* time or cost, respectively (see Row Total percentages in Table 4.2). P*ilot* and *steady-state* time and cost were nearly equal, with *steady-state* being slightly lower, reflecting slight returns on training investments made during the *pilot* phase. Total experience instructor time and cost were 1.8 and 5.2 times greater than support staff time and cost, respectively (Table 4.2). These ratios shifted across phases, with development-phase instructor time and cost being 15 and 37 times greater than that for support staff time and cost, respectively. During the latter two phases, instructor time was only 20% that of support staff, and costs were 70% that of support staff. This analysis reveals that 1) most of the personnel expenditures in this study were attributed to instructor time and cost during the *development* phase, while 2) most of the *pilot* and *steady-state* phase time and cost came from the TA. These results are expected, as the largest amount of personnel expenditures are commonly spent during the *development* phase of an experience (i.e., design planning and design execution) (Pinto, 2013).

Table 4.2

Summary of time ($T_{i\,j\,k}$) and cost (P_k) per phase, position, and task by category, in US$.

			Category					
			Instructor		Support Staff		Row Totals	
Phase	**Position**	**Task**						
Development			**161 hrs** *94%*	**$9,249** *97%*	**11 hrs** *6%*	**$248** *3%*	**171 hrs** *61%*	**$9,497** *77%*
	Admin Support Staff				**2 hrs**	**$57**	**2 hrs**	**$57**
		Capital purchase			2 hrs	$57	2 hrs	$57
	Instructor		**161 hrs**	**$9,249**			**161 hrs**	**$9,249**
		Activity design (non-tech.)	22 hrs	$1,268			22 hrs	$1,268
		Activity design/testing	36 hrs	$2,046			36 hrs	$2,046
		Capital selection	25 hrs	$1,441			25 hrs	$1,441
		Challenge design (non-tech.)	5 hrs	$288			5 hrs	$288
		Challenge design/testing	8 hrs	$461			8 hrs	$461
		Customize assessment instrument	7 hrs	$403			7 hrs	$403
		Hardware spin-up	1 hrs	$58			1 hrs	$58
		Inventory Management (devel)	5 hrs	$259			5 hrs	$259
		Investigate assessment instrument	12 hrs	$692			12 hrs	$692
		Lab setup	4 hrs	$202			4 hrs	$202
		Software spin-up	37 hrs	$2,132			37 hrs	$2,132
	Lab Tech Staff				**2 hrs**	**$66**	**2 hrs**	**$66**
		Lab setup			2 hrs	$66	2 hrs	$66
	Teaching Assistant (TA)				**7 hrs**	**$125**	**7 hrs**	**$125**
		Activity spin-up			2 hrs	$29	2 hrs	$29
		Inventory Management (devel)			5 hrs	$96	5 hrs	$96
Pilot			**12 hrs** *21%*	**$692** *44%*	**46 hrs** *79%*	**$883** *56%*	**58 hrs** *21%*	**$1,574** *13%*
	Instructor		**12 hrs**	**$692**			**12 hrs**	**$692**
		Class prep (pilot)	4 hrs	$202			4 hrs	$202
		Evaluate assessment data (pilot)	5 hrs	$259			5 hrs	$259
		Refine activity/challenge (pilot)	4 hrs	$231			4 hrs	$231
	Teaching Assistant (TA)				**46 hrs**	**$883**	**46 hrs**	**$883**
		Class prep (pilot)			4 hrs	$77	4 hrs	$77
		In-class delivery (pilot)			28 hrs	$537	28 hrs	$537
		Inventory Management (pilot)			4 hrs	$77	4 hrs	$77
		Open lab (pilot)			10 hrs	$192	10 hrs	$192
Steady-State			**8 hrs** *16%*	**$475** *36%*	**45 hrs** *84%*	**$854** *64%*	**53 hrs** *19%*	**$1,329** *11%*
	Instructor		**8 hrs**	**$475**			**8 hrs**	**$475**
		Class prep (steady-state)	6 hrs	$317			6 hrs	$317
		Inventory Management (steady-state)	1 hrs	$29			1 hrs	$29
		Open lab (steady-state)	2 hrs	$86			2 hrs	$86
		Refine activity/challenge (steady-state)	1 hrs	$43			1 hrs	$43
	Teaching Assistant (TA)				**45 hrs**	**$854**	**45 hrs**	**$854**
		In-class delivery (steady-state)			30 hrs	$576	30 hrs	$576
		Open lab (steady-state)			13 hrs	$249	13 hrs	$249
		Refine activity/challenge (steady-state)			2 hrs	$29	2 hrs	$29
Column Totals			**181 hrs** *64%*	**$10,416** *84%*	**101 hrs** *36%*	**$1,985** *16%*	**282 hrs**	**$12,401**

Ex Post Pareto: Personnel and Capital

The Pareto charts in Figure 4.1 and Figure 4.2 illustrate the tasks that were performed across the *development* and *steady-state* phases of the mechatronic experience's deployment. Examining the times per task in Figure 4.1, five (28%) were identified as vital (gray bars). These items accounted for the majority (67%) of the aggregate personnel time. Analyzing costs per task in Figure 4.2, four (22%) were identified as vital (gray bars). The first major difference evidenced by these results is the hatched bar task in Figure 4.2 (i.e., *In-class delivery (steady-state)*). The time for this task was significant, however, its associated cost was not. (It was performed by the TA position, which had the lowest calculated hourly rate.) The TA's critical role in delivering the mechatronics content should not be overlooked. Students commented in their end of semester course evaluations that the TA's in-class support (e.g., answering questions or helping troubleshoot system functionality) was significantly beneficial to their learning. The instructor performed all the other vital tasks, which included *Software spin-up, Activity design/testing, Capital selection,* and *Activity design (non-tech.)*. These results are unsurprising, due to the complexity of mechatronics systems, which require the integration of multiple technical domains (Verner & Ahlgren, 2004). From this Pareto analysis, we identified the primary personnel tasks to be tracked are the *instructor's* time and cost during the *development* and *steady-state* phases, as well as the TA's time and cost during the *steady-state* phase of an engineering education experience.

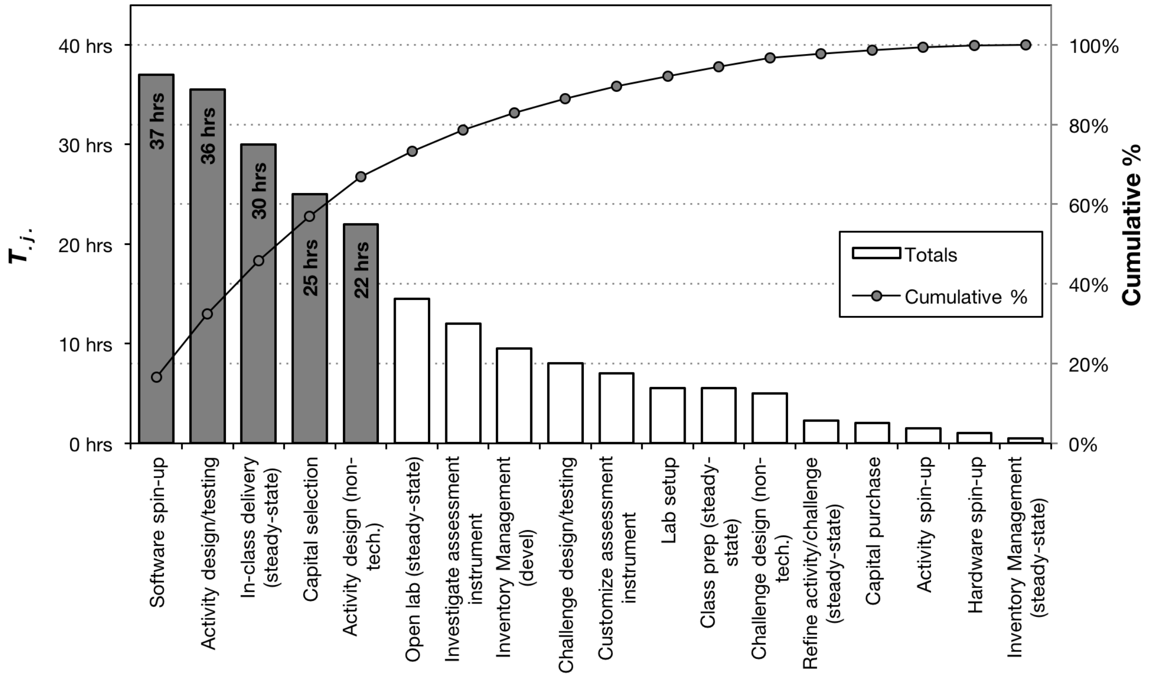

Figure 4.1

Pareto chart of personnel task time ($T_{.j.}$).

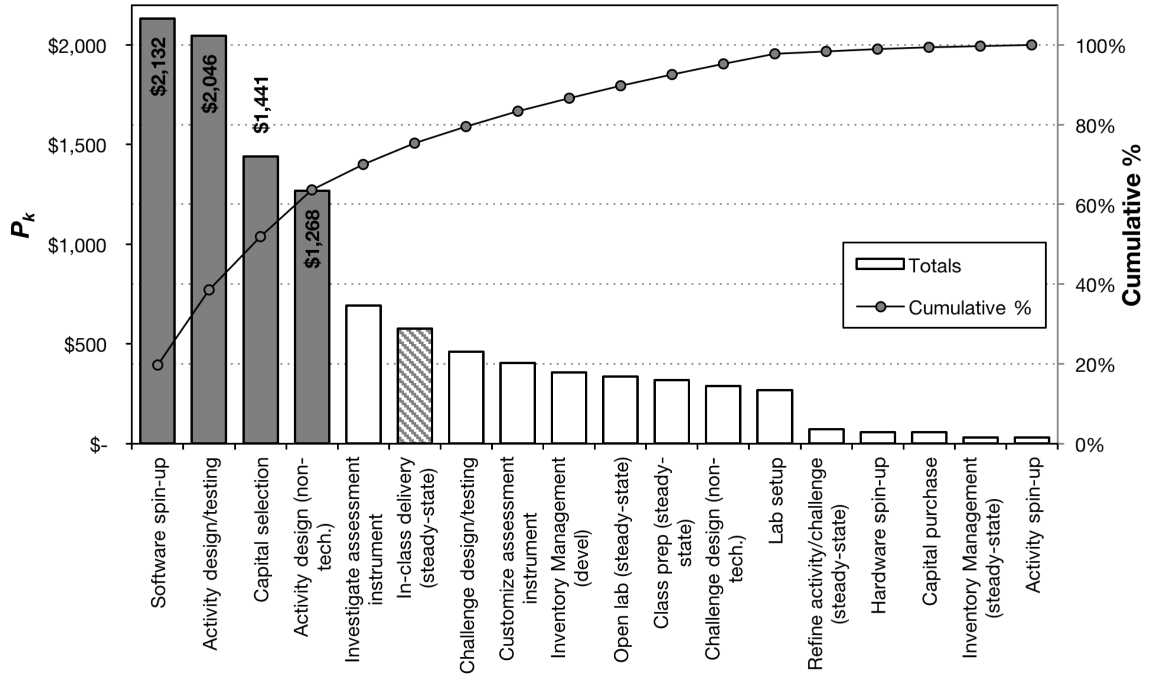

Figure 4.2

Pareto chart of personnel task cost (P_k).

Examining capital costs (*C*) per BOM item, the Pareto chart in Figure 4.3 illustrates the ZUMO robot chassis, Arduino microcontroller, and rolling storage case were the vital few (gray bars) that accounted for the significance of capital costs. These items (30%) comprised $4,117 (87%) of capital costs (Table 4.1). Apart from the storage case, this was not surprising, as the chassis and microcontroller were the most technically advanced items. Moreover, while these RP items were of primary importance from a cost perspective, their selection also drove much of the remaining BOM design (e.g., SE requirements) and affected spin-up time (e.g., software spin-up requirements) during the *development* phase. Consequently, these items were considered the primary time and cost drivers. Considering the significance of the rolling case, this item was logistically instrumental in the organization and delivery of the mechatronic experience. Speaking to more generic incremental cost analyses, we suggest (at a minimum) tracking the costs for the most “intricate”, “complex”, “advanced” pieces of equipment that are used in an experience.

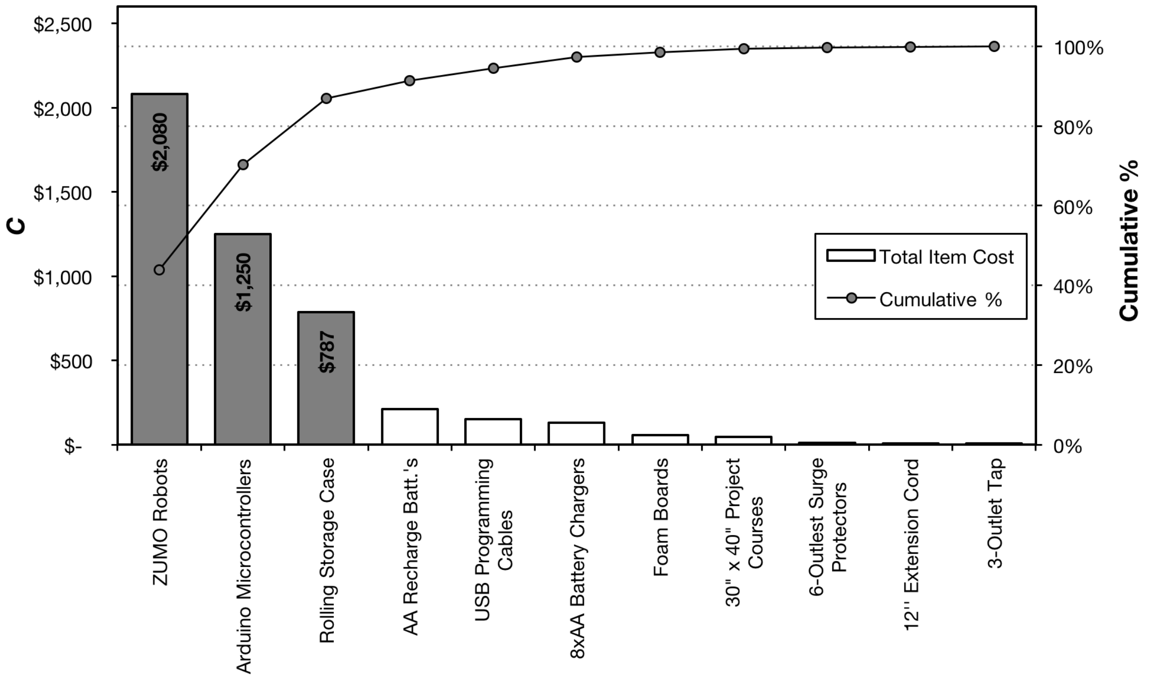

Figure 4.3
Pareto chart of capital cost (C) per BOM item.

Ex Ante Cost vs. Capacity

Personnel cost vs. seat capacity

Figure 4.4 illustrates the cost structures of per seat personnel costs (P') per yearly seat capacity (α). The scaling factor for the P' vs. α curve ($y = 883x^{-0.49}$) was close to the mean (-0.49 compared to -0.60), and well within the chemical industry's 95% interval for observations of personnel costs vs. capacity (Haldi & Whitcomb, 1967). This resulted in a range of per seat personnel costs of roughly $280 – $50, with our mechatronic experience coming in at just over $85 per seat (based on a capacity of 117 students). Specifically, personnel costs were estimated to decrease by a power of 0.49 for every additional seat, except when the capacity crosses 50 seat intervals. At these points, the P' vs. α curve has a saw-toothed profile, reflecting the discontinuous personnel costs during the *steady-state* phase of the mechatronic experience. These discontinuities occur because we added an additional instructor and TA per increment of 50 seats to the *steady-state* time. This was done to support student learning, which has been shown to be negatively correlated with section size (Hornsby & Osman, 2014). At these break points, the variable personnel costs increased by roughly \$5 – \$10 per seat, indicating possible inherent upper limits for α, similar to inherent upper physical limits of chemical process equipment (i.e., maximum allowable size) (Bonaquist, 2013). The gradual downward slope of the P' per α curve was attributed to the fixed personnel costs during the *development* phase that were amortized across the four-year estimation period. These findings support an economic rationale for increased section quantities, not section capacities. Based on this, we recommend adding class sections if seat numbers increase beyond a set class size of 50 seats for a mechatronic experience.

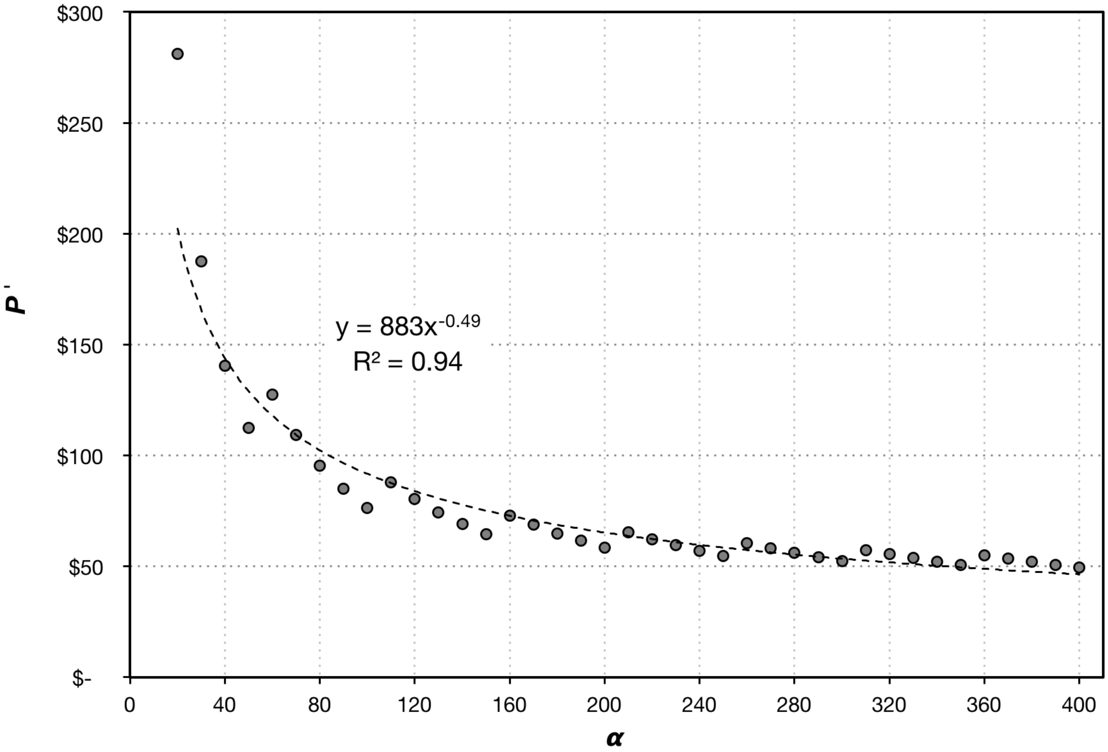

Figure 4.4
Per seat personnel costs ($\boldsymbol{P'}$) per seat capacity ($\boldsymbol{\alpha}$).

Capital cost vs. seat capacity

Estimating per seat capital costs (C') across a range of per year seat capacities (α) resulted in the cost curve in Figure 4.5. For capacities at or below the maximum section size of 50, C' per α scaled at a factor of -0.30 ($y = 467x^{-0.30}$, $R^2 = 0.99$). This means that for every additional seat (up to 50) the cost decreased by a power of 0.30. This was also within the 95% interval for observations of capital costs vs. capacity seen in the chemical processing industry (Haldi & Whitcomb, 1967). However, as the capacity increased above 50 seats, the capital costs decrease by a power of -0.99 (outside the 95% interval (Haldi & Whitcomb, 1967)) for every additional seat ($y = 6,847x^{-0.99}$, $R^2 = 1.00$). This resulted in a range of per seat capital costs of roughly \$200 – \$20, with our mechatronic experience coming in at just over \$60 per seat. Similar to the curve for personnel costs, the curve for capital costs indicated an inherent upper limit of seat capacity, which altered the economies of scale. This was not surprising, and was due to the sharing of equipment across multiple class sections, that effectively converted these to fixed costs. Therefore, to reflect this break point in α, the C' per α curve in Figure 4.5 was segmented at α = 50 to enable a more appropriate fit of the data. These results supported both the sharing of equipment across multiple course sections, which reduced the per seat cost of the mechatronic experience, and the use of multiple course sections as seat capacities are increased.

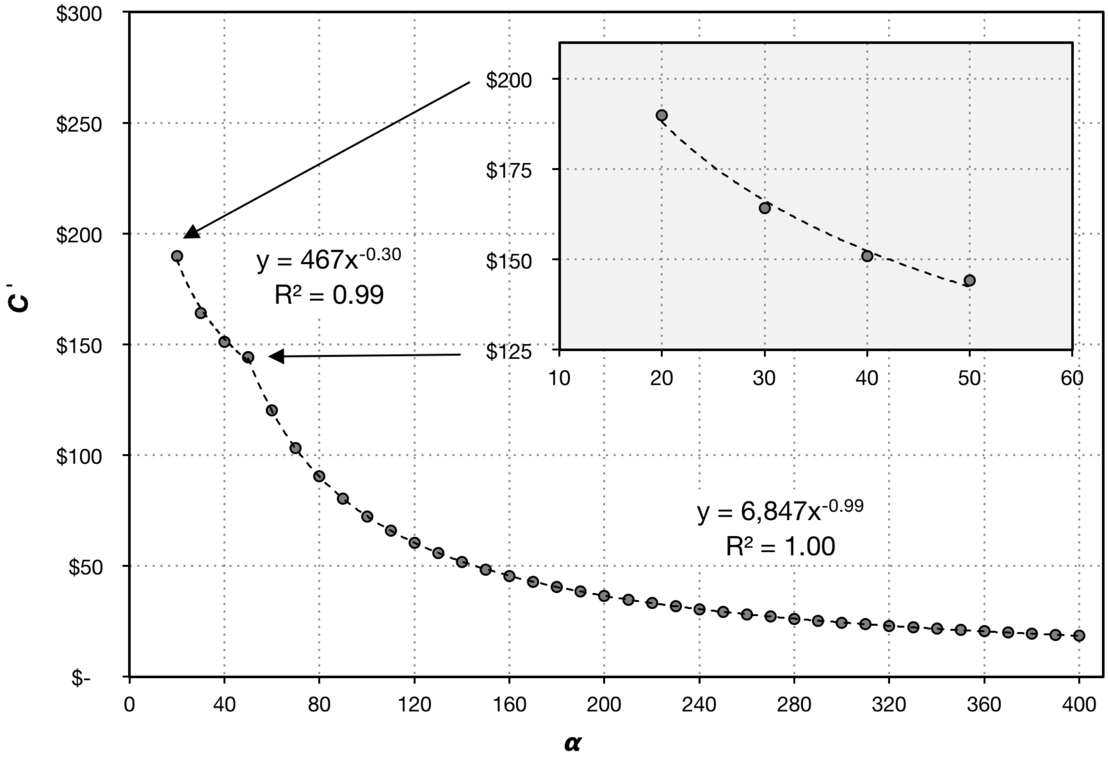

Figure 4.5
Per seat capital costs (**C'**) per seat capacity (**α**); inset chart illustrates a close-up of the cost curve of per seat capital between the capacities of 20 – 50 seats.

Total cost per seat capacity

Per seat total cost (T') per yearly seat capacity (α) is illustrated in Figure 4.6. Analysis of this figure reveals much of the same structures for fixed and variable costs as discussed for Figure 4.4 and Figure 4.5. However, unique to Figure 4.6, T' increased at a scale factor based on the combination of P' ($x^{-0.49}$) and C' ($x^{-0.89}$, *based on an* unsegmented curve) data sets. Interestingly, T' per α scaled at a factor of -0.64 ($y = 3{,}121x^{-0.64}$, $R^2 = 0.99$), which was within the expected scaling intervals for both personnel and equipment costs per capacity (Haldi & Whitcomb, 1967), and resulted in a range of per seat costs of roughly \$470 – \$70. The per seat total cost for our mechatronic experience averaging at just under \$150. The profile of this curve can be attributed to the same underlying causes as discussed above (i.e., *development* phase personnel costs being fixed and aromatized across all α while *steady-state* personnel costs varied in discrete steps of roughly $5 per seat as α increased). So, whether our data is analyzed in part or in total, there appeared to exist key break points in class size that have the potential to influence the economic (i.e., cost per seat) and logistic (i.e., personnel time per seat capacity) feasibility of implementing a mechatronic experience.

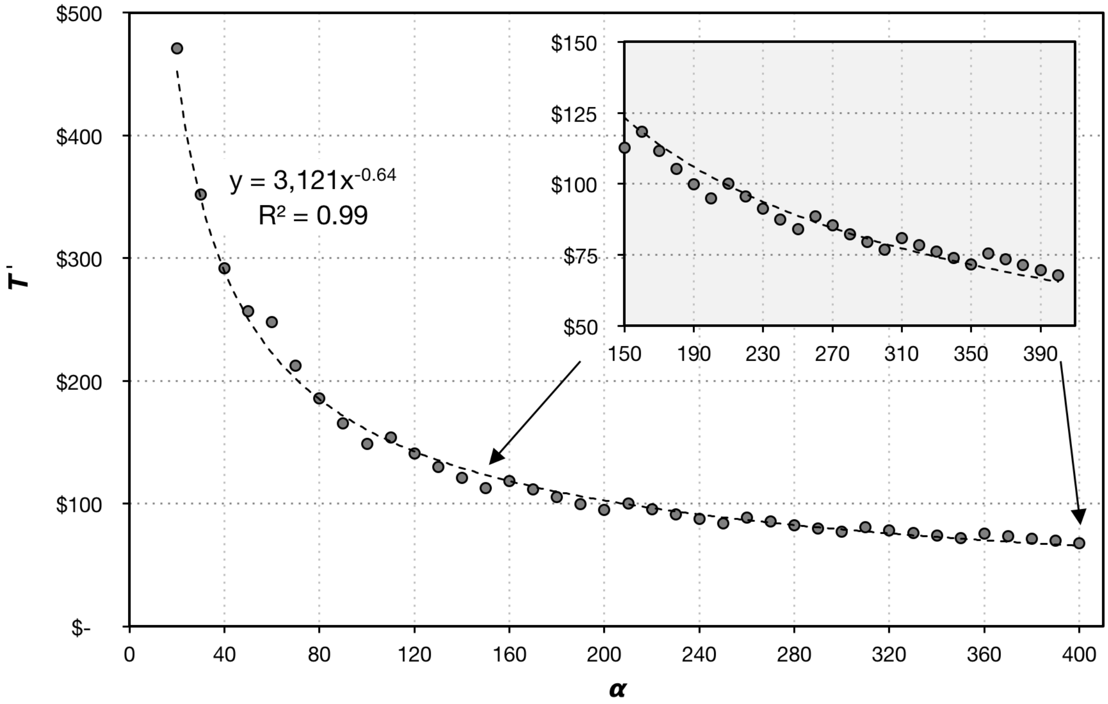

Figure 4.6
Total per seat total cost ($\boldsymbol{T'}$) per seat capacity ($\boldsymbol{\alpha}$); inset chart illustrates a close-up of the cost curve of per seat total cost between the capacities of 150 – 400 seats.

Limitations

The methods for incremental cost analysis that we used were conducted with an effort towards equity and objectivity. However, inherent limitations still exist in our methods that have the potential to affect the validity and generalizability of the results. This study did not consider intangible costs or benefits related to instructional quality or student learning outcomes, even though these factors are authentic variables in a full CBA or CEA analysis. Personnel costs (i.e., hourly rates) used in Equation 1 and 3a were contingent on the assumption made for median salaries (HigherEdJobs, 2016) and average weekly hours (Ziker, 2014). These variables will differ per institution/personnel and should be changed per usage scenario. When considering *ex ante* estimated incremental costs, the results will be heavily affected by the interest rate used to amortize across the experience's deployment period (Barnett & Escobar, 1989). Care should be taken when selecting this rate, as well as when interpreting the results. The experience level of the instructor tasked with the *development* phase design and spin-up was not included as a variable in the analysis. The instructor in this study had roughly ten years of experience in mechatronic systems integration in a variety of manufacturing and process industries, as well as three years of experience teaching fundamental engineering/technology courses. However, the instructor did not have any previous experience with the BOM items and related software tools used in this study. Finally, our power function models were estimations beyond the study's capacity sample of 121 seats. Therefore, care should be taken when generalizing these findings, as they should be considered a ±10% feasibility estimate (Pinto, 2013).

Conclusion

Recommendations

This study qualified costs and scalability of a mechatronic experience in an undergraduate course. However, we did not relate these costs, or their scalability, to an incremental effect or benefit. This future analysis would help answer real questions of cost verse impact. "Are mechatronic experiences worth it?" "Do the effects or benefits of mechatronic experiences outweigh their costs?" "What is the expected cost per unit effect or cost per unit benefit of a mechatronic experience?" These questions are important. They can and should be asked when evaluating engineering/technology education experiences. Much literature has presented evidence of effects and benefits, but limited research has combined these impacts with costs. This is evidence is needed to help answer the questions above.

Also, the variable of instructor experience is expected to affect personnel time and cost (i.e., experience inversely proportional to time and directly proportional to cost). This variability was not included in our analysis, but can affect the cost of an experience. We recommend that future research be conducted that quantifies and includes this variable in an incremental cost analysis.

Summary

In this paper, we presented a structured method of incremental cost analysis for an engineering education experience. Specifically, we proposed the collection of cost data for two of McEwan's ingredients, namely *personnel* and *equipment/materials* (Levin & McEwan, 2001). We also proposed a method for examining these costs, namely *ex post* and *ex ante* analyses. Using a representative mechatronic experience from a fundamental engineering technology course (Haughery & Raman, 2016b), we performed *ex post* descriptive, Pareto that identified the vital phases, personnel tasks, personnel categories, and capital equipment that contributed to the majority of the incremental costs of our experience. From this we found that the instructor's *development* phase time and cost, as well as the robot chassis and microcontroller capital cost were the primary economic drivers of the experience. Evaluating scaling factors, we next fit *ex ante* estimates of personnel and capital costs per yearly seat capacities using a power function model. We found that cost vs. capacity (for both personnel and capital) scaled at a factor within the 95% intervals observed in the chemical processing industry (Haldi & Whitcomb, 1967). This analysis illustrated key break points in the economic structures of the experience (i.e., cost curve profiles of Figure 4.4, Figure 4.5, and Figure 4.6). These break points were due to upper limits of seat capacity, that have the potential to positively impact the feasibility of implementing a mechatronic experience. We argue that by sharing equipment across class sections, the per seat cost can be reduced, while increased personnel time and cost is needed at key class capacity break points.

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CHAPTER 5. CONCLUSION AND RECOMMENDATIONS

Review of Objectives

Our first objective was to systematically review current literature to identify primary and secondary influences of mechatronic experiences on student engagement. To achieve this, we asked the following research question:

- What are the primary and secondary influences of mechatronic experiences on student engagement in fundamental engineering courses?

Our second objective was to quantify the differences in student motivation and academic success in a mechatronic experience vs. a non-mechatronic experience. We asked the following research questions:

- Did students in the treatment group have different levels of motivational orientation and academic success compared to those in the control group?
- Was there a difference in the proportion of students who reported being motivated in the treatment group compared to the control group?
- What was the relationship between students' motivational orientation and academic success, and did it differ in the treatment group vs. the control group?

The last objective was to quantify the costs and scalability of a mechatronic experience. We asked the following research questions:

- What incremental costs are associated with implementing a mechatronic experience?

- How do these costs scale with class size?

Review of Results

From a systematic review of current literature, we found mechatronic experiences appear to positively influence student motivation in fundamental engineering/technology courses. However, when we developed and implemented a mechatronic experience, as informed by this literature, we did not find a difference in student motivation – specifically *value choices* [$F(6,77)=0.13$, $p=0.7224$] and *expectancy beliefs* [$F(6,77)=0.38$, $p=0.5408$]. We did, however, find a statistically significant increase in mean course grades [$F(5,78)=6.51$, $p=0.0127$, $d=0.48$, $d_{95\%CI}=0.00$ to 0.98] and mean project scores [$F(5,78)=7.76$, $p=0.0067$, $d=0.70$, $d_{95\%CI}=0.20$ to 1.20] – three percentage points and eight percentage points, respectively. This experience served 121 students and cost just over $17.1k (~$12.4k for personnel and ~$4.7k for equipment), based on 2015 US$. This translated to a per seat (i.e., per student) average of just under $150 and a total cost vs. capacity scale factor of -0.64 ($y = 3{,}121x^{-0.64}$, $R^2 = 0.99$).

Recommendations and Future Work

The following recommendations were made that were beyond the scope of our research objectives. Future work is called for to realize each.

Gender Impacts

While conducting our systematic review of the influences of mechatronic experiences on student engagement, we found limited discussion focusing on gender. Only one high quality study reported differences on student engagement by gender groups. Moreover, only binary gender definitions (e.g., male or female) were used in this study. While this research was published in 2010, when these identification categories were in more common usage, current cultural norms assume a gradient of categories. Therefore, analyzing the influences of mechatronic experiences on student engagement for different gender identification categories is highly recommended.

Contextual and Experiential Impacts

We found limited evidence in the literature that explicated contextual or experiential factors. First, it was unclear from the literature how mechatronic experiences effects student engagement when considering the factor of required verse non-required course. Closely related to this was the effect that the factor of non-major verse major has. Also, it was unclear how activity type (e.g., laboratory, project, or contest) influenced student engagement. Limited evidence was found relative to learning retention, previous technical experience, or ease-of-implementation. Therefore, we recommend future research into how these factors influence or impact student engagement in a mechatronic experience.

Reporting Structure

We found a plethora of divergent reporting structures when reviewing research in engineering and technology education. While we do not intend to stifle creativity in research, we would propose a minimally consistent structure for reporting research findings. Examples of structured reporting protocols exist in the fields of epidemiology (STROBE) and medicine (CONSORT). Adopting these or similar protocols would bring a consistency and transparency to the growing field of engineering and technology education research. This in turn, would enable deeper and broader qualitative and quantitative syntheses of the “state-of-the-art” in these fields. Therefore, we recommend further research examining a practical reporting structure.

Sample Size Needs

Statistically significant differences were not found in the levels of motivation orientation between our control vs. treatment group. While we did observe higher mean scores in the treatment group, our sample sizes were not large enough to produce statistical significance. As noted in Chapter 3, there were no previous studies, to our knowledge, indicating required sample sizes or effect sizes for this phenomenon. Based on the effects for motivational orientation that we found, one would need sample sizes of roughly 800 (*expectancy beliefs*) and 2,300 (*value choices*). We recommend more research examining the effect size of mechatronic experiences on motivational orientation given these needs.

Profile Shape of Motivation

Research has indicated motivation to be dynamic throughout a project. It can peak during the middle and drop at the end. This raises several questions: Does motivation change at similar rates or degrees for mechatronic vs. non-mechatronic experiences? Are peaks in motivation the same, or do they occur at similar points in an experience? Therefore, we also recommend future research that examines the profile shape of motivational orientation over the course of a mechatronic project, not just at a pre- and post- interval.

Interaction Effect of Task Value

We did find a slight interaction between GPA and group assignment, when considering Task Value (TV). While it was not statistically significant, based on an $\alpha = 0.0063$ for repeated tests, this could indicate that higher achieving students find less value in the mechatronic experience vs. lower achieving students (*vice versa* in the control group). Could it be that the value placed on a mechatronic experience is mediated by their previous level of academic achievement (i.e., higher achieving students are less motivated by mechatronic experiences)? Again, future research is recommended to understand these relationships.

Delineation of Meaning

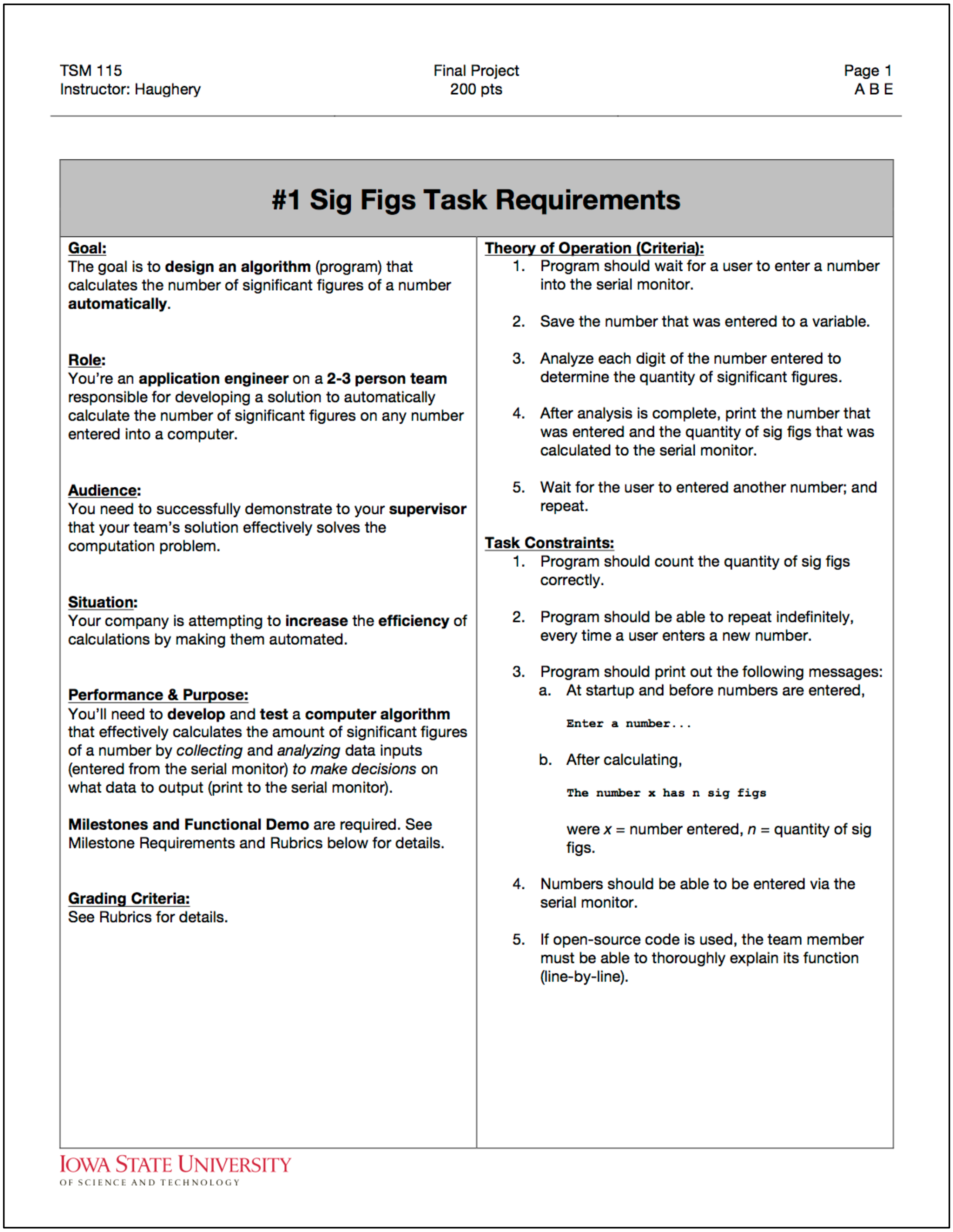
We found that students indicated the tangible and visual feedback from the mechatronic experience was why and what motivated them. While some have also indicated this, others argue that the motivational effects of these elements are simply a hallmark of project-based learning. Therefore, we recommend future research is needed to more precisely delineate between whether mechatronics specifically, or projects generally, are the qualitative force behind why and what motivates students.

Cost-Effectiveness Analysis

The methods for incremental cost analysis that we used were conducted with an effort towards equity and objectivity. However, we did not consider intangible costs or benefits related to instructional quality or student learning outcomes (i.e., improved scholarship eligibility, or improved grades). While these factors represent authentic variables in a full CBA or CEA analysis, they were beyond the scope of this study. We recommend further research to specifically delineate and quantify the outcome of academic success per costs incurred to develop, pilot, and deploy our mechatronic experience. In so doing, we would be able to define a CER for our experience based on a *post ex* analysis of the one-time and multiple year deployments, as well as *ex ante* analysis of the per seat capacities. This would allow educational decision makers to have a more correct understanding of the costs and scalability of mechatronic experiences.

Finally, we did not find incremental cost analysis methods to be common in engineering and technology education research. This was puzzling, as the economic justification of engineered products and processes is a significant element of engineering and technology fields. As funding for public higher education decreases, the need to be aware of costs and scalability of educational experiences is only more important. Therefore, we strongly recommend that researchers adopt similar methods for analyzing the costs associated with implementing educational initiatives. It would have the benefit of allowing for more robust incremental cost analyses of the effectiveness of these experiences. This could better inform curricular and policy decisions.

APPENDIX A. CONTROL EXPERIENCE TASK REQUIREMENTS



TSM 115
Instructor: Haughery

Final Project
200 pts

Page 1
A B E

#1 Sig Figs Task Requirements

Goal:
The goal is to **design an algorithm** (program) that calculates the number of significant figures of a number **automatically**.

Role:
You're an **application engineer** on a **2-3 person team** responsible for developing a solution to automatically calculate the number of significant figures on any number entered into a computer.

Audience:
You need to successfully demonstrate to your **supervisor** that your team's solution effectively solves the computation problem.

Situation:
Your company is attempting to **increase** the **efficiency** of calculations by making them automated.

Performance & Purpose:
You'll need to **develop** and **test** a **computer algorithm** that effectively calculates the amount of significant figures of a number by *collecting* and *analyzing* data inputs (entered from the serial monitor) *to make decisions* on what data to output (print to the serial monitor).

Milestones and Functional Demo are required. See Milestone Requirements and Rubrics below for details.

Grading Criteria:
See Rubrics for details.

Theory of Operation (Criteria):

1. Program should wait for a user to enter a number into the serial monitor.
2. Save the number that was entered to a variable.
3. Analyze each digit of the number entered to determine the quantity of significant figures.
4. After analysis is complete, print the number that was entered and the quantity of sig figs that was calculated to the serial monitor.
5. Wait for the user to entered another number; and repeat.

Task Constraints:

1. Program should count the quantity of sig figs correctly.
2. Program should be able to repeat indefinitely, every time a user enters a new number.
3. Program should print out the following messages:
   a. At startup and before numbers are entered,

      ```
      Enter a number...
      ```

   b. After calculating,

      ```
      The number x has n sig figs
      ```

      were *x* = number entered, *n* = quantity of sig figs.
4. Numbers should be able to be entered via the serial monitor.
5. If open-source code is used, the team member must be able to thoroughly explain its function (line-by-line).

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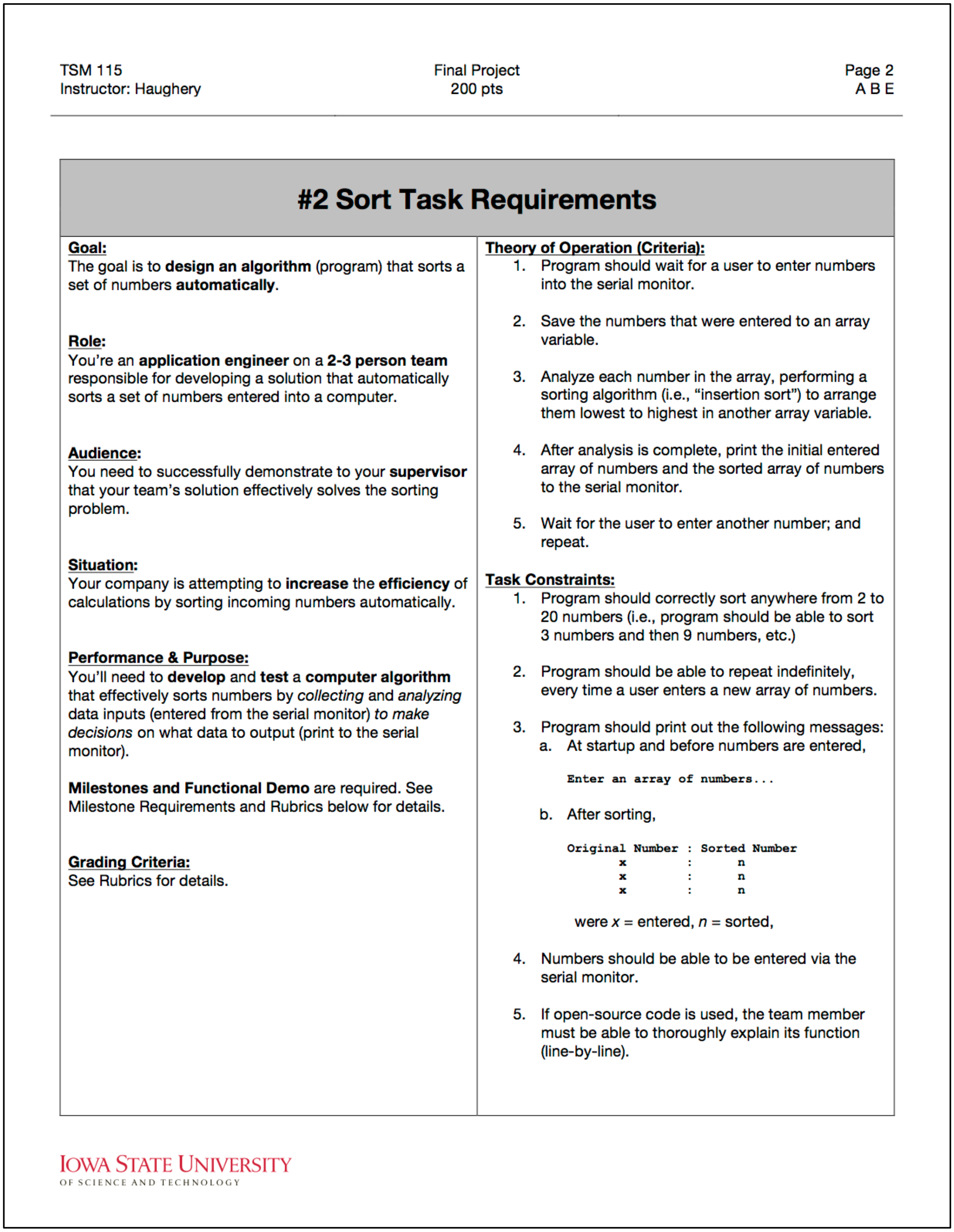
CONTROL EXPERIENCE TASK REQUIREMENTS
Continued



TSM 115
Instructor: Haughery

Final Project
200 pts

Page 2
A B E

#2 Sort Task Requirements

Goal:
The goal is to **design an algorithm** (program) that sorts a set of numbers **automatically**.

Role:
You're an **application engineer** on a **2-3 person team** responsible for developing a solution that automatically sorts a set of numbers entered into a computer.

Audience:
You need to successfully demonstrate to your **supervisor** that your team's solution effectively solves the sorting problem.

Situation:
Your company is attempting to **increase** the **efficiency** of calculations by sorting incoming numbers automatically.

Performance & Purpose:
You'll need to **develop** and **test** a **computer algorithm** that effectively sorts numbers by *collecting* and *analyzing* data inputs (entered from the serial monitor) *to make decisions* on what data to output (print to the serial monitor).

Milestones and Functional Demo are required. See Milestone Requirements and Rubrics below for details.

Grading Criteria:
See Rubrics for details.

Theory of Operation (Criteria):

1. Program should wait for a user to enter numbers into the serial monitor.
2. Save the numbers that were entered to an array variable.
3. Analyze each number in the array, performing a sorting algorithm (i.e., "insertion sort") to arrange them lowest to highest in another array variable.
4. After analysis is complete, print the initial entered array of numbers and the sorted array of numbers to the serial monitor.
5. Wait for the user to enter another number; and repeat.

Task Constraints:

1. Program should correctly sort anywhere from 2 to 20 numbers (i.e., program should be able to sort 3 numbers and then 9 numbers, etc.)
2. Program should be able to repeat indefinitely, every time a user enters a new array of numbers.
3. Program should print out the following messages:
    a. At startup and before numbers are entered,

```
Enter an array of numbers...
```

    b. After sorting,

```
Original Number : Sorted Number
         x      :       n
         x      :       n
         x      :       n
```

were *x* = entered, *n* = sorted,

4. Numbers should be able to be entered via the serial monitor.
5. If open-source code is used, the team member must be able to thoroughly explain its function (line-by-line).

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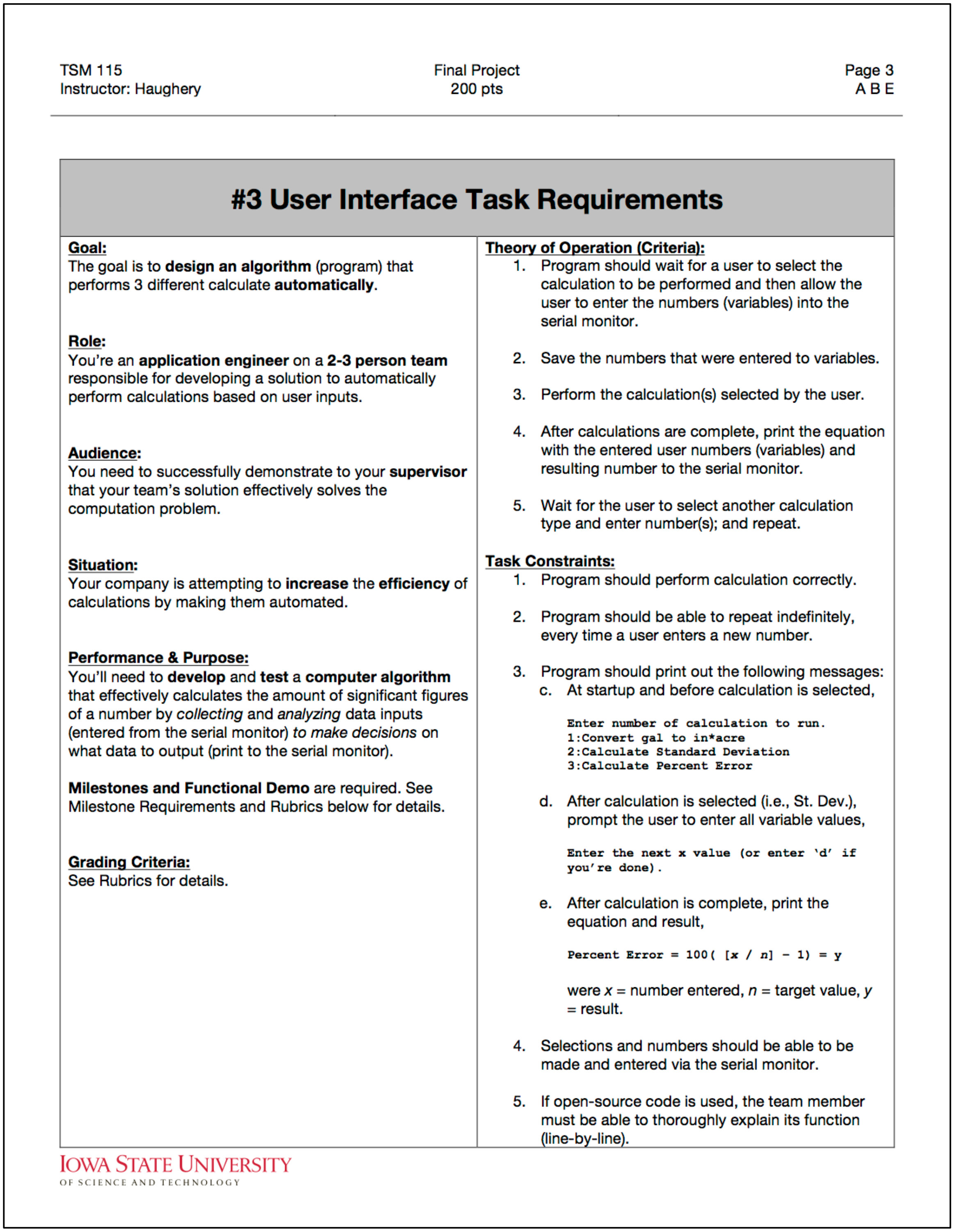
CONTROL EXPERIENCE TASK REQUIREMENTS
Continued



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Final Project
200 pts

Page 3
A B E

#3 User Interface Task Requirements

Goal:
The goal is to **design an algorithm** (program) that performs 3 different calculate **automatically**.

Role:
You're an **application engineer** on a **2-3 person team** responsible for developing a solution to automatically perform calculations based on user inputs.

Audience:
You need to successfully demonstrate to your **supervisor** that your team's solution effectively solves the computation problem.

Situation:
Your company is attempting to **increase** the **efficiency** of calculations by making them automated.

Performance & Purpose:
You'll need to **develop** and **test** a **computer algorithm** that effectively calculates the amount of significant figures of a number by *collecting* and *analyzing* data inputs (entered from the serial monitor) *to make decisions* on what data to output (print to the serial monitor).

Milestones and Functional Demo are required. See Milestone Requirements and Rubrics below for details.

Grading Criteria:
See Rubrics for details.

Theory of Operation (Criteria):

1. Program should wait for a user to select the calculation to be performed and then allow the user to enter the numbers (variables) into the serial monitor.
2. Save the numbers that were entered to variables.
3. Perform the calculation(s) selected by the user.
4. After calculations are complete, print the equation with the entered user numbers (variables) and resulting number to the serial monitor.
5. Wait for the user to select another calculation type and enter number(s); and repeat.

Task Constraints:

1. Program should perform calculation correctly.
2. Program should be able to repeat indefinitely, every time a user enters a new number.
3. Program should print out the following messages:
   c. At startup and before calculation is selected,
   ```
   Enter number of calculation to run.
   1:Convert gal to in*acre
   2:Calculate Standard Deviation
   3:Calculate Percent Error
   ```
   d. After calculation is selected (i.e., St. Dev.), prompt the user to enter all variable values,
   ```
   Enter the next x value (or enter 'd' if
   you're done).
   ```
   e. After calculation is complete, print the equation and result,
   ```
   Percent Error = 100( [x / n] – 1) = y
   ```
   were *x* = number entered, *n* = target value, *y* = result.
4. Selections and numbers should be able to be made and entered via the serial monitor.
5. If open-source code is used, the team member must be able to thoroughly explain its function (line-by-line).

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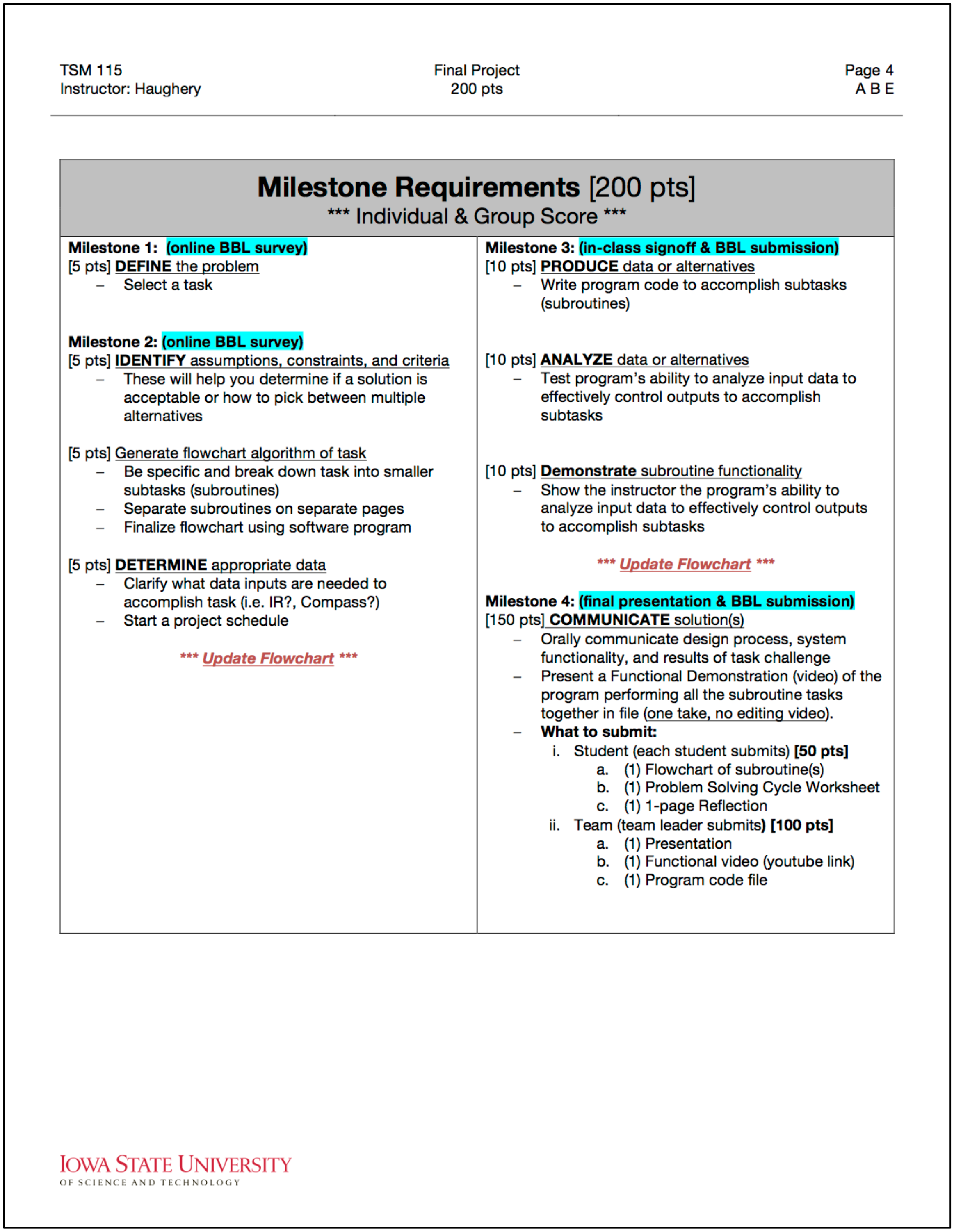
CONTROL EXPERIENCE TASK REQUIREMENTS
Continued



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Final Project
200 pts

Page 4
A B E

Milestone Requirements [200 pts]
*** Individual & Group Score ***

Milestone 1: (online BBL survey)
[5 pts] **DEFINE** the problem
- Select a task

Milestone 2: (online BBL survey)
[5 pts] **IDENTIFY** assumptions, constraints, and criteria
- These will help you determine if a solution is acceptable or how to pick between multiple alternatives

[5 pts] Generate flowchart algorithm of task
- Be specific and break down task into smaller subtasks (subroutines)
- Separate subroutines on separate pages
- Finalize flowchart using software program

[5 pts] **DETERMINE** appropriate data
- Clarify what data inputs are needed to accomplish task (i.e. IR?, Compass?)
- Start a project schedule

****** Update Flowchart ******

Milestone 3: (in-class signoff & BBL submission)
[10 pts] **PRODUCE** data or alternatives
- Write program code to accomplish subtasks (subroutines)

[10 pts] **ANALYZE** data or alternatives
- Test program's ability to analyze input data to effectively control outputs to accomplish subtasks

[10 pts] **Demonstrate** subroutine functionality
- Show the instructor the program's ability to analyze input data to effectively control outputs to accomplish subtasks

****** Update Flowchart ******

Milestone 4: (final presentation & BBL submission)
[150 pts] **COMMUNICATE** solution(s)
- Orally communicate design process, system functionality, and results of task challenge
- Present a Functional Demonstration (video) of the program performing all the subroutine tasks together in file (one take, no editing video).
- **What to submit:**
  - i. Student (each student submits) **[50 pts]**
    - a. (1) Flowchart of subroutine(s)
    - b. (1) Problem Solving Cycle Worksheet
    - c. (1) 1-page Reflection
  - ii. Team (team leader submits) **[100 pts]**
    - a. (1) Presentation
    - b. (1) Functional video (youtube link)
    - c. (1) Program code file

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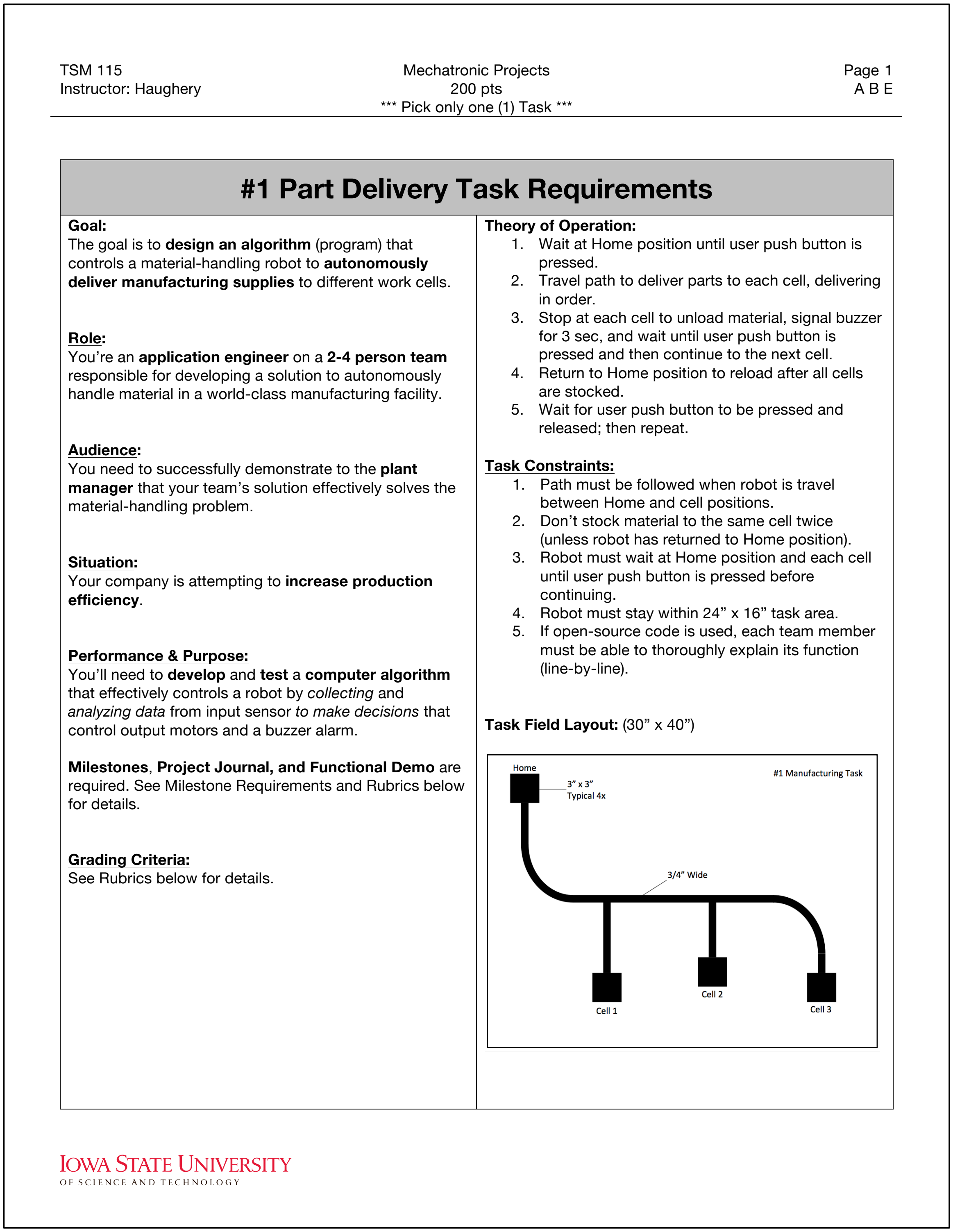
APPENDIX B. TREATMENT EXPERIENCE TASK REQUIREMENTS



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Mechatronic Projects
200 pts
*** Pick only one (1) Task ***

Page 1
A B E

#1 Part Delivery Task Requirements

Goal:
The goal is to **design an algorithm** (program) that controls a material-handling robot to **autonomously deliver manufacturing supplies** to different work cells.

Role:
You're an **application engineer** on a **2-4 person team** responsible for developing a solution to autonomously handle material in a world-class manufacturing facility.

Audience:
You need to successfully demonstrate to the **plant manager** that your team's solution effectively solves the material-handling problem.

Situation:
Your company is attempting to **increase production efficiency**.

Performance & Purpose:
You'll need to **develop** and **test** a **computer algorithm** that effectively controls a robot by *collecting* and *analyzing data* from input sensor *to make decisions* that control output motors and a buzzer alarm.

Milestones, **Project Journal, and Functional Demo** are required. See Milestone Requirements and Rubrics below for details.

Grading Criteria:
See Rubrics below for details.

Theory of Operation:
1. Wait at Home position until user push button is pressed.
2. Travel path to deliver parts to each cell, delivering in order.
3. Stop at each cell to unload material, signal buzzer for 3 sec, and wait until user push button is pressed and then continue to the next cell.
4. Return to Home position to reload after all cells are stocked.
5. Wait for user push button to be pressed and released; then repeat.

Task Constraints:
1. Path must be followed when robot is travel between Home and cell positions.
2. Don't stock material to the same cell twice (unless robot has returned to Home position).
3. Robot must wait at Home position and each cell until user push button is pressed before continuing.
4. Robot must stay within 24" x 16" task area.
5. If open-source code is used, each team member must be able to thoroughly explain its function (line-by-line).

Task Field Layout: (30" x 40")

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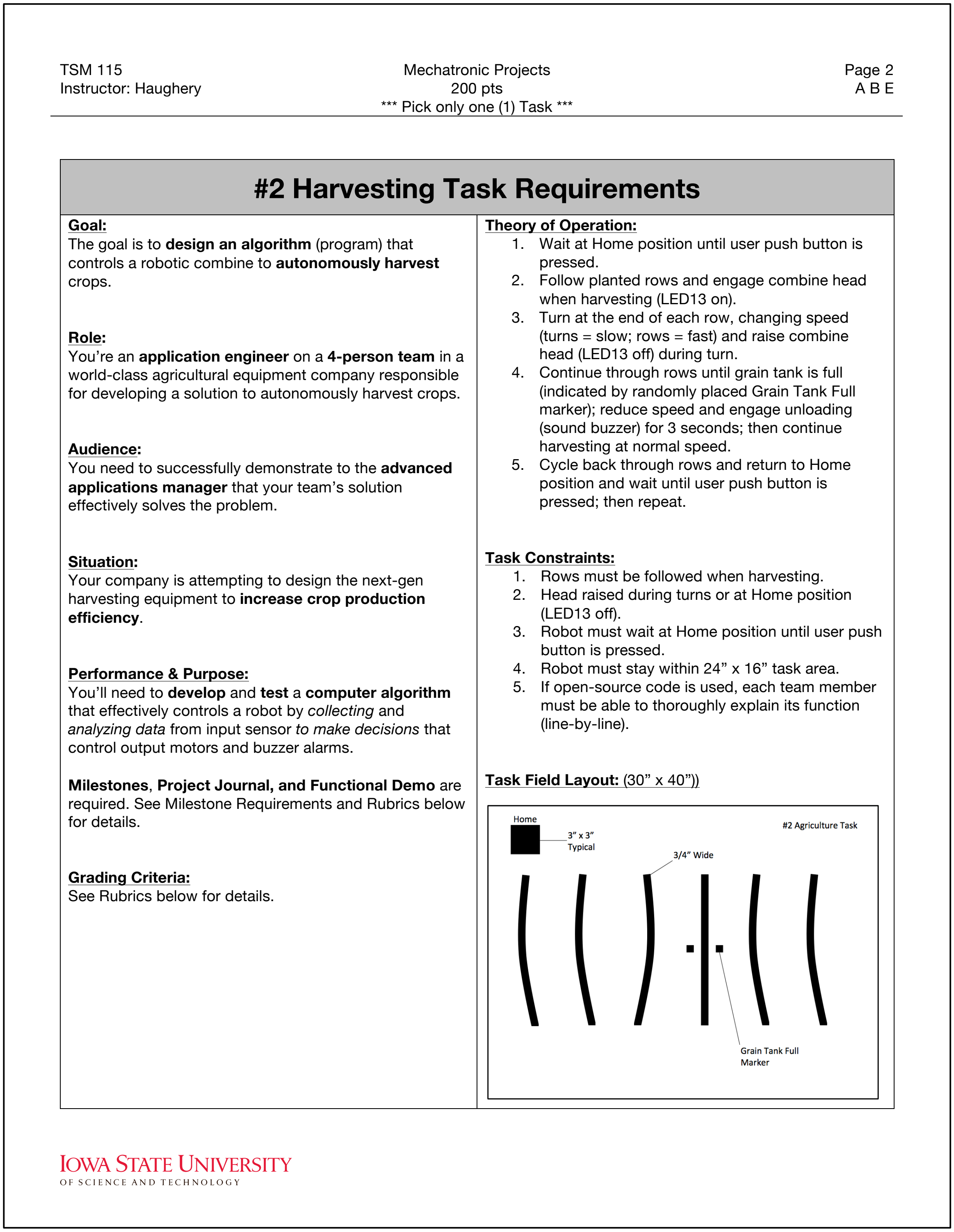
TREATMENT EXPERIENCE TASK REQUIREMENTS
Continued



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Mechatronic Projects
200 pts
*** Pick only one (1) Task ***

Page 2
A B E

#2 Harvesting Task Requirements

Goal:
The goal is to **design an algorithm** (program) that controls a robotic combine to **autonomously harvest** crops.

Role:
You're an **application engineer** on a **4-person team** in a world-class agricultural equipment company responsible for developing a solution to autonomously harvest crops.

Audience:
You need to successfully demonstrate to the **advanced applications manager** that your team's solution effectively solves the problem.

Situation:
Your company is attempting to design the next-gen harvesting equipment to **increase crop production efficiency**.

Performance & Purpose:
You'll need to **develop** and **test** a **computer algorithm** that effectively controls a robot by *collecting* and *analyzing data* from input sensor *to make decisions* that control output motors and buzzer alarms.

Milestones, **Project Journal, and Functional Demo** are required. See Milestone Requirements and Rubrics below for details.

Grading Criteria:
See Rubrics below for details.

Theory of Operation:

1. Wait at Home position until user push button is pressed.
2. Follow planted rows and engage combine head when harvesting (LED13 on).
3. Turn at the end of each row, changing speed (turns = slow; rows = fast) and raise combine head (LED13 off) during turn.
4. Continue through rows until grain tank is full (indicated by randomly placed Grain Tank Full marker); reduce speed and engage unloading (sound buzzer) for 3 seconds; then continue harvesting at normal speed.
5. Cycle back through rows and return to Home position and wait until user push button is pressed; then repeat.

Task Constraints:

1. Rows must be followed when harvesting.
2. Head raised during turns or at Home position (LED13 off).
3. Robot must wait at Home position until user push button is pressed.
4. Robot must stay within 24" x 16" task area.
5. If open-source code is used, each team member must be able to thoroughly explain its function (line-by-line).

Task Field Layout: (30" x 40"))

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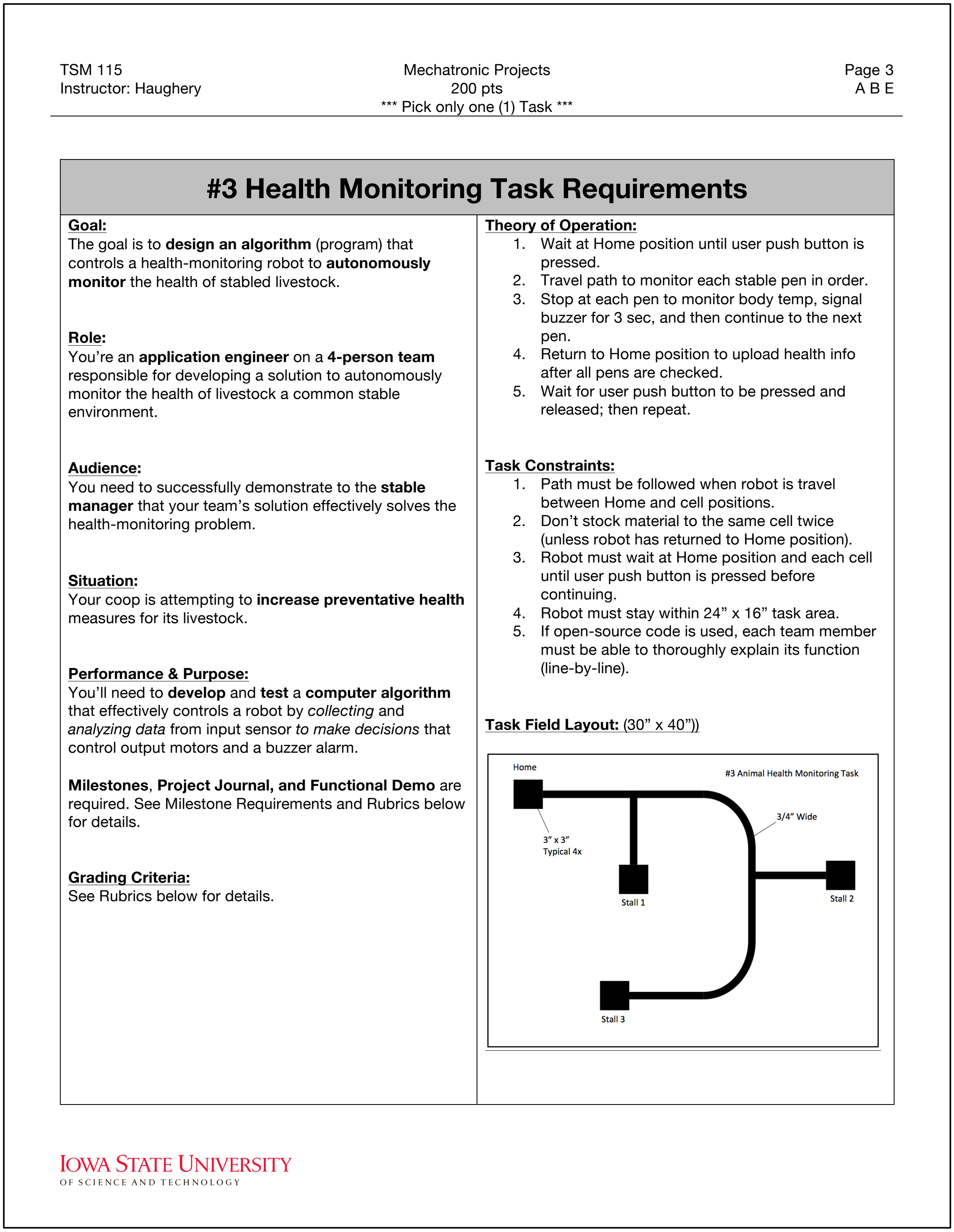
TREATMENT EXPERIENCE TASK REQUIREMENTS
Continued



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Mechatronic Projects
200 pts
*** Pick only one (1) Task ***

Page 3
A B E

#3 Health Monitoring Task Requirements

Goal:
The goal is to **design an algorithm** (program) that controls a health-monitoring robot to **autonomously monitor** the health of stabled livestock.

Role:
You're an **application engineer** on a **4-person team** responsible for developing a solution to autonomously monitor the health of livestock a common stable environment.

Audience:
You need to successfully demonstrate to the **stable manager** that your team's solution effectively solves the health-monitoring problem.

Situation:
Your coop is attempting to **increase preventative health** measures for its livestock.

Performance & Purpose:
You'll need to **develop** and **test** a **computer algorithm** that effectively controls a robot by *collecting* and *analyzing data* from input sensor *to make decisions* that control output motors and a buzzer alarm.

Milestones, **Project Journal, and Functional Demo** are required. See Milestone Requirements and Rubrics below for details.

Grading Criteria:
See Rubrics below for details.

Theory of Operation:
1. Wait at Home position until user push button is pressed.
2. Travel path to monitor each stable pen in order.
3. Stop at each pen to monitor body temp, signal buzzer for 3 sec, and then continue to the next pen.
4. Return to Home position to upload health info after all pens are checked.
5. Wait for user push button to be pressed and released; then repeat.

Task Constraints:
1. Path must be followed when robot is travel between Home and cell positions.
2. Don't stock material to the same cell twice (unless robot has returned to Home position).
3. Robot must wait at Home position and each cell until user push button is pressed before continuing.
4. Robot must stay within 24" x 16" task area.
5. If open-source code is used, each team member must be able to thoroughly explain its function (line-by-line).

Task Field Layout: (30" x 40"))

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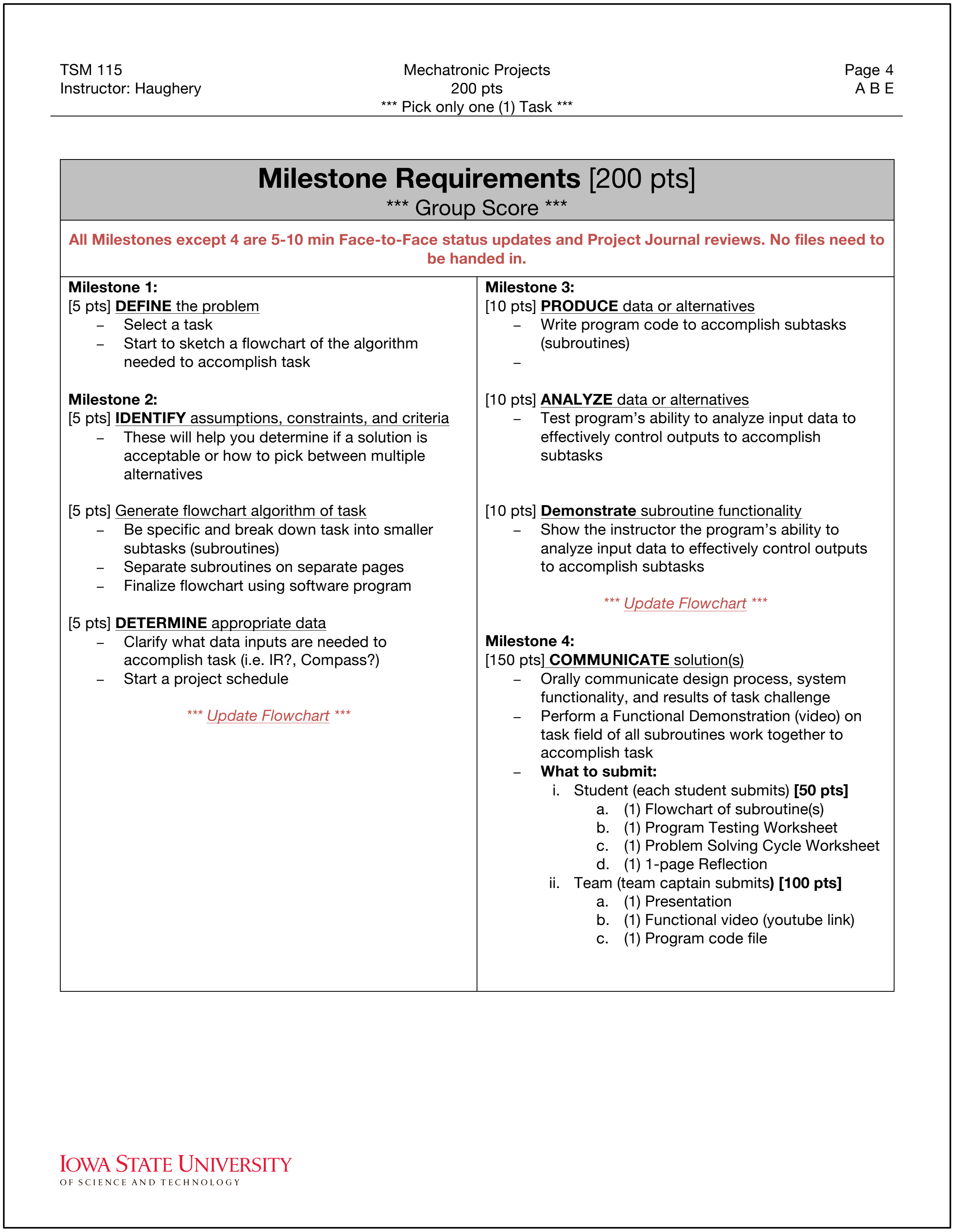
TREATMENT EXPERIENCE TASK REQUIREMENTS
Continued



TSM 115
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Mechatronic Projects
200 pts
*** Pick only one (1) Task ***

Page 4
A B E

Milestone Requirements [200 pts]
*** Group Score ***

All Milestones except 4 are 5-10 min Face-to-Face status updates and Project Journal reviews. No files need to be handed in.

Milestone 1:
[5 pts] **DEFINE** the problem
- Select a task
- Start to sketch a flowchart of the algorithm needed to accomplish task

Milestone 2:
[5 pts] **IDENTIFY** assumptions, constraints, and criteria
- These will help you determine if a solution is acceptable or how to pick between multiple alternatives

[5 pts] Generate flowchart algorithm of task
- Be specific and break down task into smaller subtasks (subroutines)
- Separate subroutines on separate pages
- Finalize flowchart using software program

[5 pts] **DETERMINE** appropriate data
- Clarify what data inputs are needed to accomplish task (i.e. IR?, Compass?)
- Start a project schedule

*** *Update Flowchart* ***

Milestone 3:
[10 pts] **PRODUCE** data or alternatives
- Write program code to accomplish subtasks (subroutines)
-

[10 pts] **ANALYZE** data or alternatives
- Test program's ability to analyze input data to effectively control outputs to accomplish subtasks

[10 pts] **Demonstrate** subroutine functionality
- Show the instructor the program's ability to analyze input data to effectively control outputs to accomplish subtasks

*** *Update Flowchart* ***

Milestone 4:
[150 pts] **COMMUNICATE** solution(s)
- Orally communicate design process, system functionality, and results of task challenge
- Perform a Functional Demonstration (video) on task field of all subroutines work together to accomplish task
- **What to submit:**
  i. Student (each student submits) **[50 pts]**
    a. (1) Flowchart of subroutine(s)
    b. (1) Program Testing Worksheet
    c. (1) Problem Solving Cycle Worksheet
    d. (1) 1-page Reflection
  ii. Team (team captain submits**) [100 pts]**
    a. (1) Presentation
    b. (1) Functional video (youtube link)
    c. (1) Program code file

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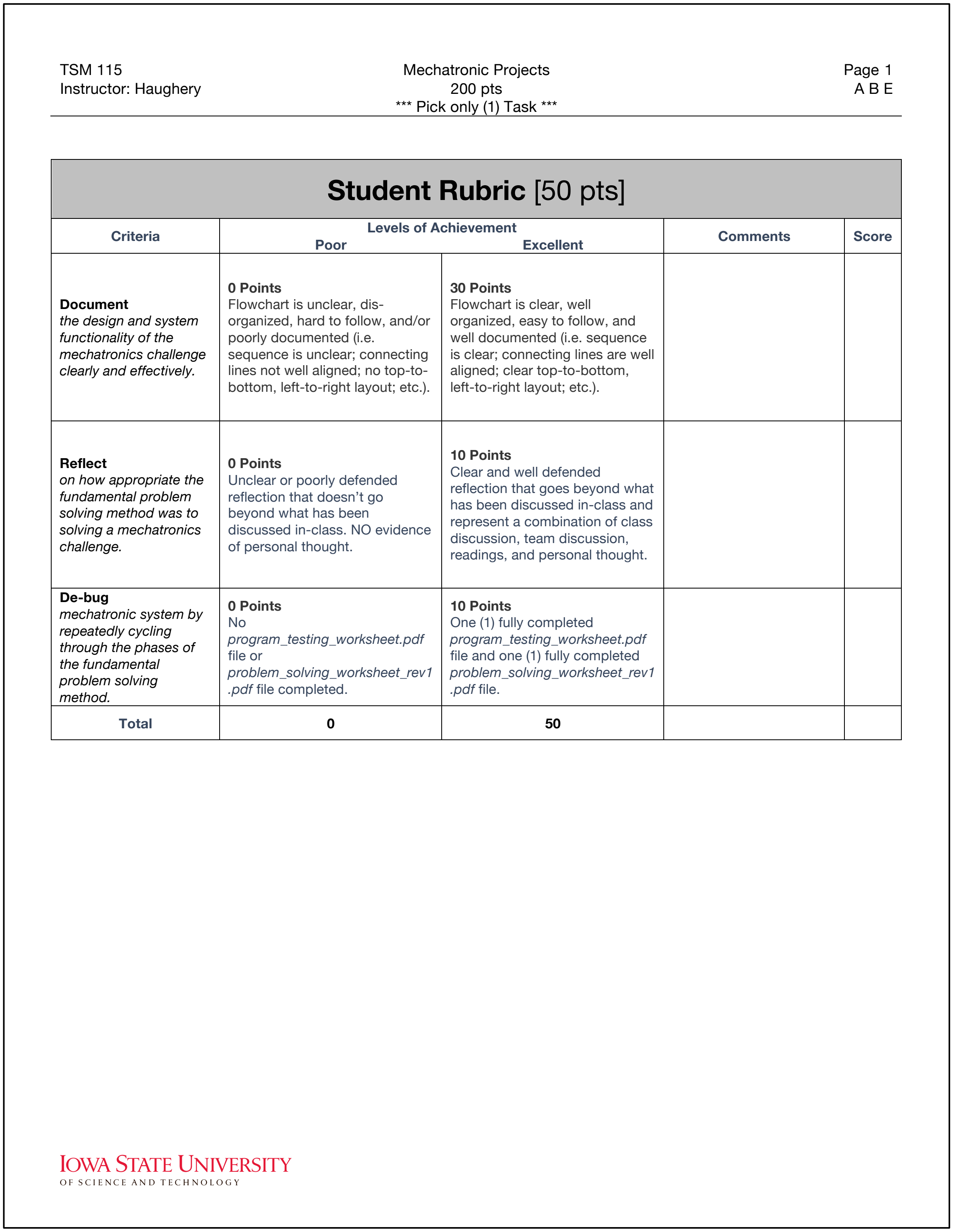
APPENDIX C. CONTROL AND TREATMENT TASK GRADING RUBRIC

(MILESTONE 4)



TSM 115
Instructor: Haughery

Mechatronic Projects
200 pts
*** Pick only (1) Task ***

Page 1
A B E

Student Rubric [50 pts]

Criteria	Levels of Achievement		Comments	Score
	Poor	Excellent		
Document *the design and system functionality of the mechatronics challenge clearly and effectively.*	**0 Points** Flowchart is unclear, dis-organized, hard to follow, and/or poorly documented (i.e. sequence is unclear; connecting lines not well aligned; no top-to-bottom, left-to-right layout; etc.).	**30 Points** Flowchart is clear, well organized, easy to follow, and well documented (i.e. sequence is clear; connecting lines are well aligned; clear top-to-bottom, left-to-right layout; etc.).		
Reflect *on how appropriate the fundamental problem solving method was to solving a mechatronics challenge.*	**0 Points** Unclear or poorly defended reflection that doesn't go beyond what has been discussed in-class. NO evidence of personal thought.	**10 Points** Clear and well defended reflection that goes beyond what has been discussed in-class and represent a combination of class discussion, team discussion, readings, and personal thought.		
De-bug *mechatronic system by repeatedly cycling through the phases of the fundamental problem solving method.*	**0 Points** No *program_testing_worksheet.pdf* file or *problem_solving_worksheet_rev1.pdf* file completed.	**10 Points** One (1) fully completed *program_testing_worksheet.pdf* file and one (1) fully completed *problem_solving_worksheet_rev1.pdf* file.		
Total	**0**	**50**		

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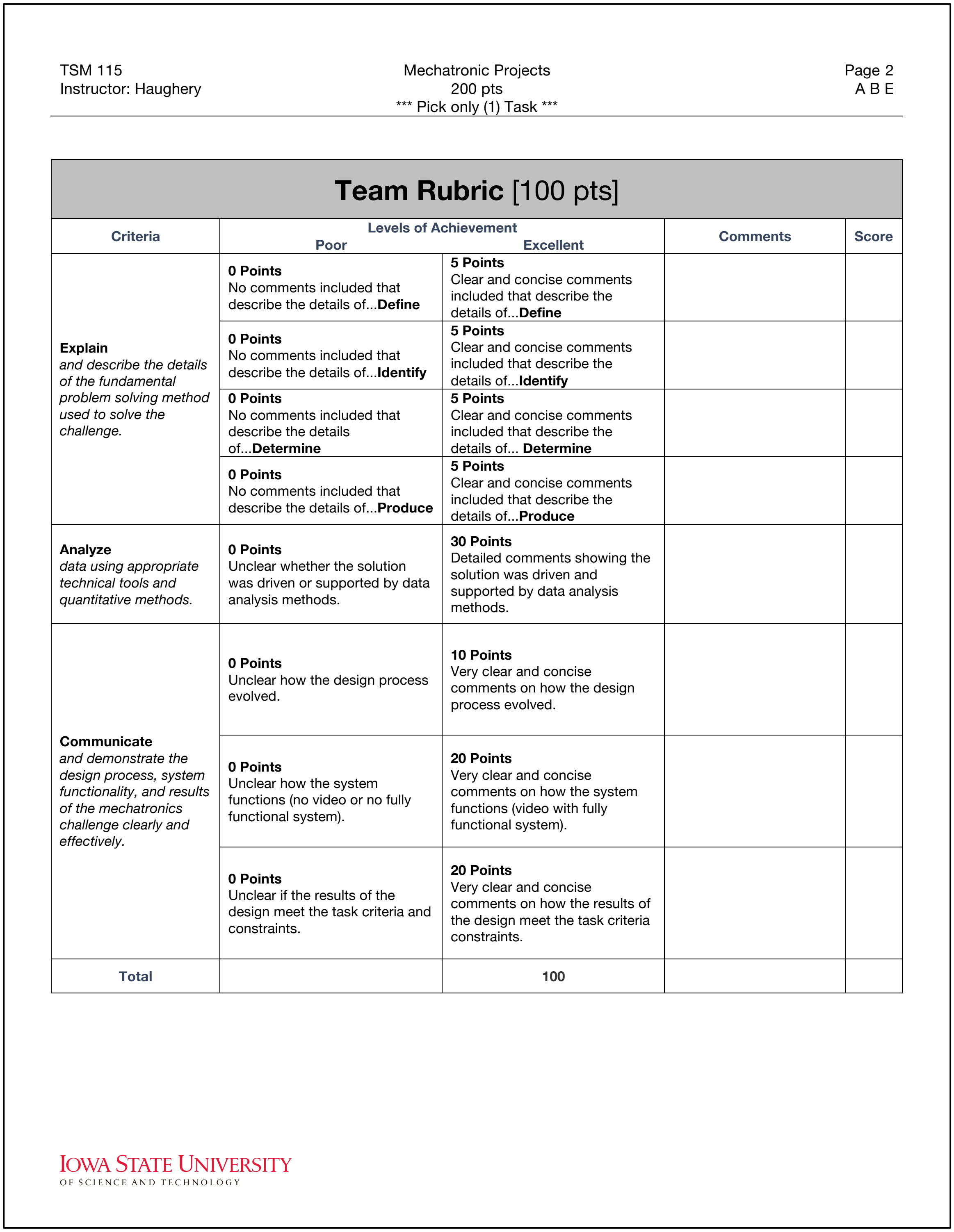
CONTROL AND TREATMENT TASK GRADING RUBRIC

(MILESTONE 4)
Continued



TSM 115
Instructor: Haughery

Mechatronic Projects
200 pts
*** Pick only (1) Task ***

Page 2
A B E

Team Rubric [100 pts]

Criteria	Levels of Achievement		Comments	Score
	Poor	Excellent		
Explain *and describe the details of the fundamental problem solving method used to solve the challenge.*	**0 Points** No comments included that describe the details of...**Define**	**5 Points** Clear and concise comments included that describe the details of...**Define**		
	0 Points No comments included that describe the details of...**Identify**	**5 Points** Clear and concise comments included that describe the details of...**Identify**		
	0 Points No comments included that describe the details of...**Determine**	**5 Points** Clear and concise comments included that describe the details of... **Determine**		
	0 Points No comments included that describe the details of...**Produce**	**5 Points** Clear and concise comments included that describe the details of...**Produce**		
Analyze *data using appropriate technical tools and quantitative methods.*	**0 Points** Unclear whether the solution was driven or supported by data analysis methods.	**30 Points** Detailed comments showing the solution was driven and supported by data analysis methods.		
Communicate *and demonstrate the design process, system functionality, and results of the mechatronics challenge clearly and effectively.*	**0 Points** Unclear how the design process evolved.	**10 Points** Very clear and concise comments on how the design process evolved.		
	0 Points Unclear how the system functions (no video or no fully functional system).	**20 Points** Very clear and concise comments on how the system functions (video with fully functional system).		
	0 Points Unclear if the results of the design meet the task criteria and constraints.	**20 Points** Very clear and concise comments on how the results of the design meet the task criteria and constraints.		
Total		**100**		

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APPENDIX D. TASKS PER POSITION

Table D1

Description of estimated median salaries per personnel position, rounded to nearest hundred dollar.

Position	Median Salary*
Instructor	$83,800
Teaching Assistant	$26,500
Lab Technical Staff	$45,500
Administrative Support Staff	$39,200

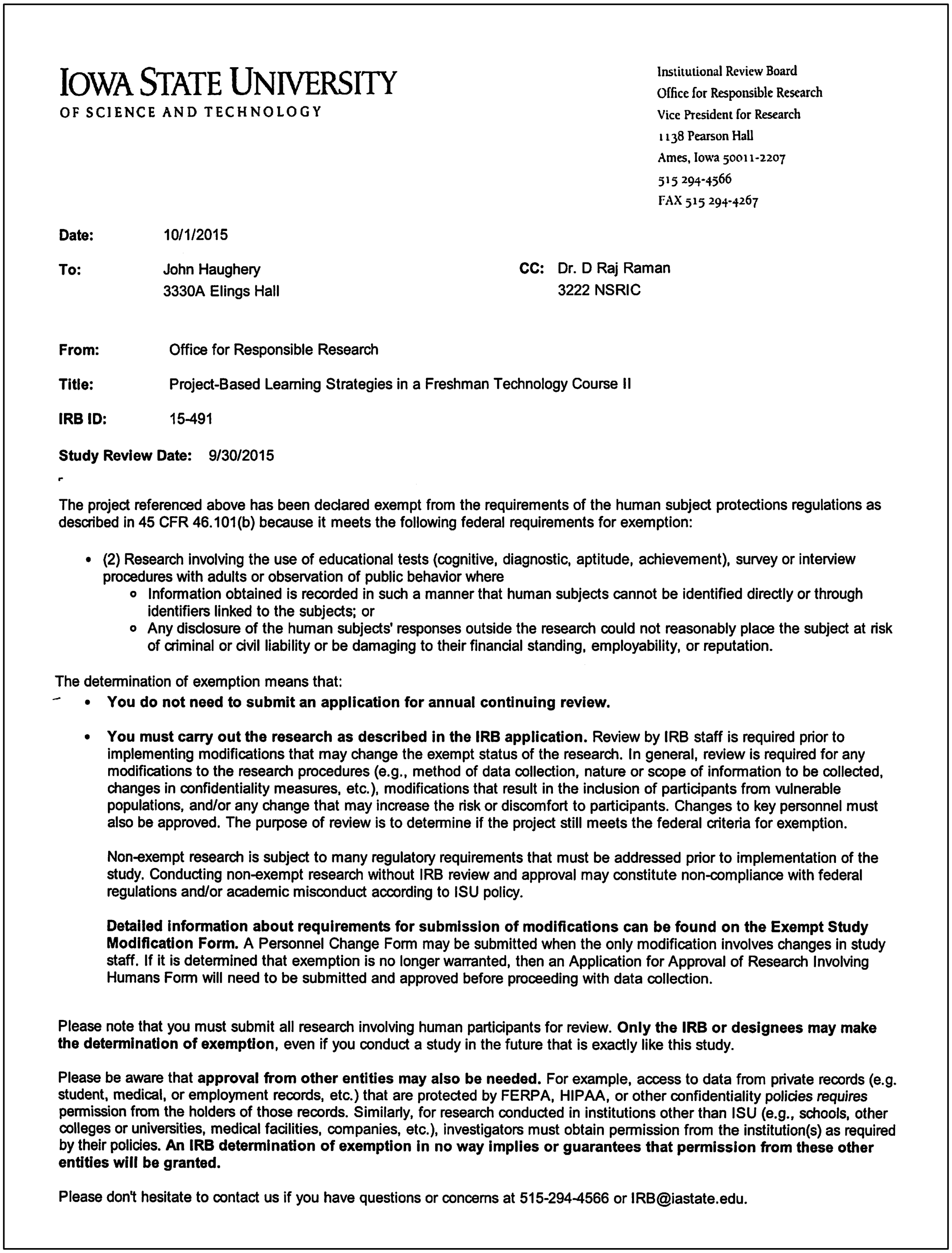
**Source*: CUPA-HR Salary Surveys, 2015-16 (HigherEdJobs, 2016).

APPENDIX E. TASKS PER PHASE AND POSITION

Table E1
Description of tasks performed during each phase of the mechatronic experience.

Development	Pilot	Steady-State	Suggested Minimal Tracking	Task	Description
√			√	Capital selection	Selection of lab equipment
√				Capital purchase	Purchasing of lab equipment
√				Hardware spin-up	Becoming acquainted with hardware platform (i.e. Arduino UNO board)
√			√	Software spin-up	Becoming acquainted with software environment (i.e. Arduino IDE)
√			√	Activity design (non-tech.)	Design of weekly lab activities that DID NOT focus on hardware/software elements
√				Project design (non-tech.)	Design of final project that DID NOT focus on hardware/software elements
√			√	Activity design/testing	Design and testing of weekly lab activities that DID focus on hardware/software elements
√				Project design/testing	Design and testing of final project that DID focus on hardware/software elements
√				Lab setup	Preliminary setup of lab to facility mechatronic experience
√				Activity spin-up	Becoming acquainted with activities (teaching assistants)
√				Investigate assessment instrument	Research into appropriate assessment instrument to use to measure student motivation
√				Customize assessment instrument	Modification of selected assessment instrument custom use
√	√			Inventory Management	Storage and organization of lab equipment (i.e. robot chassis)
	√	√	√	In-class delivery	Additional effort to deliver mechatronic experience labs and project
	√	√		Open lab	Extra open labs specific to mechatronic labs and final project
	√	√		Class prep	Weekly class preparations during mechatronic experience delivery
	√	√		Evaluate assessment data	Analyze effects of mechatronic experience on student motivation
	√	√		Refine activity/challenge	Reflection and revision of mechatronic labs and final projects

APPENDIX F. INSTITUTIONAL REVIEW BOARD EXEMPT APPROVAL



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Institutional Review Board
Office for Responsible Research
Vice President for Research
1138 Pearson Hall
Ames, Iowa 50011-2207
515 294-4566
FAX 515 294-4267

Date: 10/1/2015

To: John Haughery
3330A Elings Hall

CC: Dr. D Raj Raman
3222 NSRIC

From: Office for Responsible Research

Title: Project-Based Learning Strategies in a Freshman Technology Course II

IRB ID: 15-491

Study Review Date: 9/30/2015

The project referenced above has been declared exempt from the requirements of the human subject protections regulations as described in 45 CFR 46.101(b) because it meets the following federal requirements for exemption:

- (2) Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey or interview procedures with adults or observation of public behavior where
  - Information obtained is recorded in such a manner that human subjects cannot be identified directly or through identifiers linked to the subjects; or
  - Any disclosure of the human subjects' responses outside the research could not reasonably place the subject at risk of criminal or civil liability or be damaging to their financial standing, employability, or reputation.

The determination of exemption means that:

- **You do not need to submit an application for annual continuing review.**

- **You must carry out the research as described in the IRB application.** Review by IRB staff is required prior to implementing modifications that may change the exempt status of the research. In general, review is required for any modifications to the research procedures (e.g., method of data collection, nature or scope of information to be collected, changes in confidentiality measures, etc.), modifications that result in the inclusion of participants from vulnerable populations, and/or any change that may increase the risk or discomfort to participants. Changes to key personnel must also be approved. The purpose of review is to determine if the project still meets the federal criteria for exemption.

  Non-exempt research is subject to many regulatory requirements that must be addressed prior to implementation of the study. Conducting non-exempt research without IRB review and approval may constitute non-compliance with federal regulations and/or academic misconduct according to ISU policy.

  Detailed information about requirements for submission of modifications can be found on the Exempt Study Modification Form. A Personnel Change Form may be submitted when the only modification involves changes in study staff. If it is determined that exemption is no longer warranted, then an Application for Approval of Research Involving Humans Form will need to be submitted and approved before proceeding with data collection.

Please note that you must submit all research involving human participants for review. **Only the IRB or designees may make the determination of exemption**, even if you conduct a study in the future that is exactly like this study.

Please be aware that **approval from other entities may also be needed.** For example, access to data from private records (e.g. student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies *requires* permission from the holders of those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. **An IRB determination of exemption in no way implies or guarantees that permission from these other entities will be granted.**

Please don't hesitate to contact us if you have questions or concerns at 515-294-4566 or IRB@iastate.edu.