EXPANDING ENGINEERING DESIGN WITH MINI PROJECTS – THEORY OF MECHANISMS A PILOT COURSE

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Abstract – In order to expand the instruction of engineering design in courses that are predominantly engineering science, the Chair in Design Engineering of the University of Victoria has launched a program to introduce design mini-projects. The development and management of these projects is conducted by the course instructor in collaboration with a Design Teaching Assistant. The first design mini-project has been developed for Theory of Mechanisms, a third-year core-course in Mechanical Engineering. The course is primarily theoretical and includes four laboratory projects that are based on deterministic problems. In order to establish an appropriate project, a list of learning objectives that complements the theoretical content of the course and exposes students to an engineering design problem has been identified. The project consists in designing and building an automaton for young children – a mechanical toy operated by a hand crank. Overall the project was successful, students rapidly embraced it, the submitted prototypes generally met or exceeded our expectations, and the learning objectives were achieved.

Keywords: Engineering Design Mini Project, Theory of Mechanisms, Automata, Mechanical Toy, Teaching Assistance Guidance, Synthesis of Mechanisms.

1. INTRODUCTION

As recipients of an NSERC Chair in Design Engineering, the UVic Faculty of Engineering is implementing programs to improve and expand the instruction of engineering design within undergraduate courses. One initiative is to find courses that are primarily engineering science and introduce mini-projects in engineering design. Design problems are inherently non-deterministic with multiple acceptable solutions [1]. Within engineering courses, teams of undergraduate students are given design problems that they must solve by working together. From this, students are exposed to

all the challenges associated with the design process and teamwork.

The mechanical engineering curriculum at the University of Victoria includes two core design courses in the first year, one core design course in the second year, one core design course in the third year, and one capstone design course in the fourth year. Despite the already strong engineering design program in the existing curriculum, there is a need to promote engineering design in courses that are predominantly engineering science. The design projects for these courses, in contrast to the already established design courses, should be less demanding and focus on concepts related to the course.

The development and management of these projects will be conducted by the course instructor in collaboration with a Design Teaching Assistant (DTA). A DTA is a graduate student who satisfactorily completed a training course called Design Engineering & Instruction [2]. This training course is focused on three critical aspects: Fundamentals of engineering design, mentoring teams of undergraduate students, and development of engineering design mini projects.

The first mini-design project was developed for Theory of Mechanisms (MECH 335), a course taught in the first term of the third year in the Mechanical Engineering program. The course is primarily theoretical and includes four laboratory projects that are based on deterministic problems. The course is structured to teach the kinematics and dynamics of each mechanism (linkages, cams, gears), separately.

Traditionally, the first term of the third year (3A) is one of the most demanding terms as other core courses (Mechanics of Solids II, Mechanics of Fluids, Energy Conversion, Numerical Analysis and Engineering Design) are taught at the same time. During this term, a number of students join the university program after completing successfully a two-year college-level technology program. Therefore, not all the students are familiar with each other, and more importantly, the formation of these students is diverse. While university formed students have a stronger theoretical background, college formed students have a stronger hands-on skill.

2. PROJECT DEVELOPMENT

2.1. Learning Objectives

In order to establish a mini-project that aligns with the objectives of the course and promotes engineering design, a number of learning objectives were established:

Group Formation: Teams will be formed randomly in groups of up to four students. By randomly selecting the students, a better real life situation is simulated [3]. This selection will prevent students to be left alone without a group. Also, critical diversity will be encouraged, as students that already know are often reluctant to be too critical of their friends' work [4].

Project Management: Teams have limited time to complete the conceptualization and assembly of their project. Teams should be prepared to establish a well defined timeline that will allow them to complete their projects on time.

Project Requirements: In order to align the project with the course content a number of project requirements should be considered. However, students should have an ample choice in relation to these requirements.

Creative Project: The project should promote creativity in students. An open-ended design problem where students define the theme of their choice should provide the opportunity to develop innovative and original ideas, as well as it should promote ownership and enthusiasm of their own design concepts.

Design Objectives and Constraints: Students should identify the design objectives and design constraints of their own concepts.

Motion Transmission: Students should learn about transmitting motion through different components. In the course lectures each mechanism is studied independently and these individual mechanisms are never combined to create a mechanical machine. Transmitting motion through multiple mechanisms complements the material covered in class.

Mechanism Function: Students will have to explore the functions of different mechanisms. When students conceptualize an idea, they will have to find ways to create such motion. There are particular mechanisms that could provide such motion.

Synthesis and Optimization: Students will learn about synthesizing and optimizing mechanisms. Some of the required movements have to be very precise, whether because the mechanisms have to be synchronized with the motion of other components or because they have to follow a particular path. Thus the design of mechanisms has to be carefully determined (optimized).

Troubleshooting: Design is an iterative process. Testing design concepts is a critical step of the design process. Prototypes require constant troubleshooting to fix

the flaws encountered [5]. Students will learn to solve problems that were not originally envisioned.

Reflection: Since there is limited time for this project, it is expected that not all the components work properly. However, students should learn to analyze their work and present a reflection of how their project can be improved. This diagnostic analysis is part of the iteration process carried out in the design process.

2.2. Project Selection

The selection of the design project was not only based on finding a project in which the learning objectives could be easily implemented but also the project had to be accomplished within the timeframe available. Moreover, students had to have sufficient skills/background and easy access to resources (mechanical components, materials, use of design facilities, and computer software).

The timeframe was dictated by the workload in other courses as well as the allotted time for this course in the design facilities. Since the project of the design core course in this term (Engineering Design) had a priority to use the design/manufacturing facilities, it was important not to overlap the two projects.

Although the project could have been developed using computer software exclusively, we thought that students would learn more about the design process if they had to build a prototype that could be tested exposing the flaws of their concepts. The manufacturing facility was not available to us due to the high demand during that period. However, we were able to have access to a design studio which is equipped with sufficient tools for wood crafting.

Based on these constraints and the list of learning objectives, the selected project was the design and construction of an **automaton**.

Rigorously speaking, an automaton (*pl. automata*) is a self-operating machine. Automata have existed for many years. There are records of automata from ancient Greece (Hero of Alexandria), Judea, China, Persia and India. Ancient automata were operated with wind, water and fire. Medieval Islamic engineers left marvelous books of ingenious mechanical devices (Al-Jazari). During the Renaissance, numerous clockwork devices were manufactured and automata designs were sketched (Leonardo da Vinci). During the industrial revolution, mechanical clocks and ingenious toys were built. The Golden Age of Automata occurred in the 19th century. Automata may be considered the legacy of modern robots.

Nowadays, the term automaton is also referred to "story telling mechanical sculptures" that are manually operated by turning a crank. This definition was incorporated to the project, as students had to build a manually operated automaton for young children, i.e. a wooden mechanical toy.

By specifying that the automaton had to be a mechanical toy for young children, students have to identify particular design objectives and constraints associated to children and their operational use, e.g., appropriate story, type of automaton (recreational or educational), safety, ease of operation, robustness, etc.

Designing and building automata for educational purposes has been done from elementary school [6-7] to university projects [8]. The learning objectives at each level are different. The Clockwork objects, enhanced learning: Automata Toys Construction (CLOHE) program founded by the European Union Life Long Learning Programme is dedicated to introduce automata to elementary school children with the objective of building transversal key competences (engineering, arts, sculpture, mechanics and science). For first-year university students the learning, designing and building an automaton exposes the students to think in three dimensions [8].

2.3. Project Management

This project was assigned for the first time in the spring of 2013 (92 students, 24 teams). Students had 10 weeks to work on this project. Students received marginal guidance from the instructor and a teaching assistant, who was not trained as a DTA, and met the groups twice during term. In 2014 (115 students, 30 teams), the time given to the teams was cut down to only 5 weeks due to the increase in the enrollment that limited the allotted time of this course within the design facilities.

In order for the students to complete their project within a very short time, it was necessary to provide greater assistance from the instructor and the DTA, first and second authors of this paper. One strategy was to buy components, such as spur gears, bevel gears, shafts, worm gears, collars, and pulleys. These mechanical components were hand-built or acquired by the students in 2013 and they spent significant time doing this. We managed to obtain scrap pieces such as gears and shafts from old printers. We also bought sets of gears and pulleys from VEX Robotics Inc., a company that produces robotics kits. One reason of adopting the VEX components was

their high durability and that the Faculty already owns multiple of these kits that are used for other courses. Therefore, if one specific component was required, it was possible to borrow it from their existing inventory.

Also, we look for local facilities where the students could work or produce particular pieces that were difficult to craft, e.g. 3D printing.

Since the allotted time for the use of the facilities occurred in the first five weeks of the term, it was necessary to introduce some of the potential mechanisms to be used as well as their functions. The DTA introduced the mechanisms and functions during a one-hour tutorial in the first week of the term and a potential team calendar (Table 1) was proposed. In the early lectures, students also learned basic concepts of mechanism synthesis.

The DTA scheduled weekly meetings of 10-15 minutes long with every team until the deadline of the project. The purpose of the first meeting (second week) was to meet each team, assess the team formation and guide them through the conceptualization of the automata. In the meeting, the project requirements were revised, students assigned project responsibilities, and the students were notified that a peer and self assessment was going take place at the end of the project. Peer- and self-assessments are used to measure the individuals' team performance. This is a technique that is employed both in industry and universities to evaluate the contribution and accountability of each team member [9-10]. This assessment is more significant when the groups have been formed randomly. When students form their own teams, they are agreeing *a priori* about their accountability. During the first two weeks of the term, a number of students dropped the course (students found a co-op position). In order to maintain the teams with three or four members, teams had to be re-arranged accordingly.

The other two scheduled meetings were 15 minutes long and the DTA ensured that the students were working together as a team and that progress was aligned with the expectations of the calendar. During these two weeks, teams identified the mechanical components that required and these components were distributed. Any missing component was borrowed from the Faculty's inventory.

Table 1: Proposed Project Calendar for the Five Week Period.

Week 1 (Jan 6-10)	Week 2 (Jan 13 - 17)	Week 3 (Jan 20 - 24)	Week 4 (Jan 27 - 31)	Week 5 (Feb 3 - 6)
Team Formation Research: Mechanisms Machines Mechanism Function Team Brainstorm	Define: Objectives Constraints Individual Design Concepts Design Selection Motion Transmission	Subsystem Definition Interconnection Mechanism Development Request (commercial components and 3D printing)	CAD Design System Integration Workspace Coordination Structure Fabrication Subsystem Assembly	Subsystem Testing System Assembly System Testing Final Verification Preliminary Documentation
Tutorial	Scheduled Meeting	Scheduled Meeting	Scheduled Meeting	Due Date

3. AUTOMATON DESIGN PROJECT

3.1. Project Requirements

Problem Statement:

Design and build an automaton, preferably made out of wood, in the form of a mechanical toy for young children that tells a story.

Prototype Requirements:

- Employ at least two families of mechanisms: linkages (four- and six bars), slider cranks, cams, gears, Geneva wheels, Scotch Yoke mechanism, etc.
- Have at least four mechanisms.
- Have at least six animated components that will move to 'tell a story'.
- All these components must move by manually turning a crank.
- Special mechanical components (Geneva mechanisms, gears, pulleys, etc.) can be 3D printed or purchased.
- Budget: Teams must not exceed \$80.00 CAD dollars.

Report Requirements:

- Specify the design objectives and constraints.
- Design alternatives (At least three concepts with sketches, description and discussion).
- Design selection method, final design description, and CAD design (avoid particular details).
- Motion flow chart, i.e. a flow chart from the crank to all the components.
- Displacement analysis (Displacement graph of crank vs. animated component).
- Velocity analysis (Velocity graph of crank vs. animated component).
- Testing/Evaluation.
- Reflection.

In general, a course project is submitted at the end of the course allowing students to apply all the knowledge gained during the term. However, due to the large workload of other courses from week six to the end of the term, it was necessary to complete the prototype early in the term. Nonetheless, the submission of the report is due near the end of the term. In doing so, it was possible to use the project as a real problem of motion transmission in which the mechanisms had to be analyzed. Two major analyses are requested: Displacement and velocity analyses. Linkages were analyzed using loop-closure equations [11]. The displacement of a cam follower was carried out using mathematical functions: constant velocity, parabolic (constant acceleration), simple harmonic and cycloidal [11]. Gears were analyzed using the fundamental law of tooth gearing (constant speed ratio). Geneva wheels were analyzed analytically [12]. Had the analysis been conducted prior to designing the automata, some students would have design their

automaton based on the simplicity in which the mechanisms are analyzed.

As a continuation of the iterative nature of the design process, the reflection section is a critical aspect of the final report. Here, students have to describe how they would improve their automaton. What changes they would make if they had to design it and build it again.

3.2. Results

The project was successful. Students rapidly embraced the project with enthusiasm, the submitted prototypes passed our expectations, and the learning objectives were met. Despite being a mini-project that is worth only 20% of the final grade, students were passionate about their projects and clearly showing hard work and dedication.

Figures 1-6 show six examples of the built prototypes. The concepts were original and different from each other.

Fig. 1. Lighthouse powered by step motor. Courtesy of Adam Poulson, Andy Garland, Graeme Ramsay, and Sheng Huaiyuan.

Fig. 2. Jousting Knights. Courtesy of Steve Delorme, Trevor Grier, Alberto Galleguillos, and Elvis Tchetga.

Fig. 3. Horse (Theo Jansen's concept). Courtesy of Aakash Rao, Michael Cox, Osman Ulluocak, Joseph Lowther.

Fig. 4. Sailboat Race. Courtesy of Edward Alley, Ryan Carter, Hunter MacDonald, and Phillip Tchernov.

Fig. 5. T-Rex Dinosaur. Courtesy of Doug Braden, Angus Rittenburg, Darren Fry, and Rio Whyte.

Fig. 6. Steamboat Willie. Courtesy of Lucas Karperian, Kalonica Christie, and Solomon McMorran.

Although, gears (spur, bevel, worm, and crown), cams, pulleys and four-bars were the most frequent types of mechanisms, also chains, Geneva wheels, Scotch yoke, and six bar mechanisms were used in multiple designs.

A general problem among teams was the significant time spent fixing problems during the assembly phase. These problems had not been identified in the conceptualization phase or even in the preliminary design phase where the simulations of the CAD models worked as expected. However, once the prototype was built, the transmission of motion failed in different places. A common mistake occurred with the misalignment of the follower stem using cams, which would produce high side thrust and frictional forces. The experience of facing these problems shows the importance of developing prototypes that expose some of the conceptual flaws.

3.3. Project Assessment

As oppose to most of the engineering design projects where the design goals are well defined, here the objective goals are defined by the same students. As the range of complexity and creativity between projects can be significant, assessing a project like this is not simple.

Engineering design projects are usually evaluated with rubrics. Once developed, a rubric facilitates the evaluation process [13]. Rubrics define the criteria for assessment, qualities that will be assessed, and identify the levels of performance that students might demonstrate for each quality [14]. Therefore, it is necessary to identify performance objectives. These were identified on four major categories: Design Conceptualization, Final Design, Documentation and Reflection, and Teamwork. The rubrics of the assessment are given in the appendix.

Design Conceptualization. Here students have to identify the design objectives and constraints. Making young children as the end users creates a number of

objectives to be analyzed. At least three alternative concepts have to be reported. Each member develops and presents a design concept to the team, these are discussed and a method of selection is conducted. The creative use of mechanisms and storytelling is also assessed.

Final Design. Here students have to demonstrate the effectiveness of transmitting motion, the ease of operational use, complexity of the design (the range of complexity of all projects is significant), robustness, appearance and signs of testing and troubleshooting.

Documentation and Reflection. Here students are assessed for the analysis of their design, drawings and sketches, general documentation, and the reflection of how they would improve their automata.

Teamwork. Since the teams are formed randomly, there is potential for friction between the members of a team. Thus, individual students are self and peer assessed.

3.4. Project Recommendations

Although the project was a success, students enjoyed designing and building the automata, there are some recommendations that should be considered in the future.

Safety. Not all the students have worked with powered tools. Although no accidents occurred, it was noticed that students could be somewhat careless with the use of powered tools. In the future, it would be beneficial to have a tutorial of the use of powered tools before the students begin building their automata.

Time. A goal was to reduce the building time from +20 hours/person in 2013 to 12 hours in 2014. We failed to do so; the average time was very similar. We expected that by providing mechanical components the construction time was going to decrease; however, the overall quality of the automata improved considerably. Since students elevated their standards, we will have to reschedule a laboratory that coincided with the project's initial weeks.

4. CONCLUSIONS

Teams of undergraduate students work together to design and build a functional prototype in limited time. However, it is expected not to fully achieve some desired objectives e.g., functionality, operational ease, aesthetics, etc. Instead students are expected to engage with the complexity of making engineering design decisions, whether creative, functional, or even troubleshooting. Overall, this project provides a complete experience in engineering design and complements the theoretical content of the course.

Acknowledgements

The authors wish to thank the Natural Sciences and Engineering Council of Canada (NSERC) through the

Chairs in Design Engineering Program for the financial support.

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APPENDIX: ASSESSMENT RUBRIC

	Topic	Unacceptable (0)		Marginal (1)		Satisfactory (2)		Commendable (2.5)		Exceptional (3)		Weight
Design Conceptualization	Design Objectives / Appropriateness	No valid objectives or inappropriate for children		One or two valid objectives & somehow inappropriate		Two valid objectives or somehow inappropriate		Two-three valid objectives and appropriate		More valid objectives and appropriate		1.5
	Creative Thinking of Story Telling	Reproduction (copy)		Adaptation (similar to existing)		Original with two major animated components telling story		Original with all components telling the story.		Exceptional originality, sync multiple animated components.		1
	Alternative Concepts	No valid concepts		One valid concept		Two valid concepts		Three valid concepts		Three valid concepts (one exceptional)		1
	Design Requirements	Only one family of mechanisms		Under four mechanisms		Missing some animated components		Missing one animated component		Meet requirements		1.5
	Creative use of Mechanisms	Unacceptable use of mechanisms		Marginal use of mechanisms (too simplistic)		Acceptable use of mechanisms (serial driven)		Commendable use of mechanisms (parallel driven)		Exceptional use of mechanisms (special mechanisms)		1
	Selection of Concept Design	No decision is made		Decision is not justified.		Decision is justified but is not objective.		Decision is justified and somehow objective		Decision is well justified and objective		1
Final Design	Functionality	Incapable to transmit motion		Motion transmission fails in multiple places		Motion transmission continuously fails in one place		Motion transmission occasionally fails in one place		Motion is transmitted with ease		3
	Operational Use	Cannot operate		Crank is really stiff		Crank is stiff		Crank is somehow stiff		Crank turns effortlessly		1
	Complexity of Final Design	Lack of creativity and complexity		Basic transmission. Dissociated animated components.		Acceptable design transmission for one major component		Acceptable design transmission for two major components		Exceptional design transmission for three major components		1.5
	Robustness	Prototype falls apart		Poor construction, it shows serious signs for failure		Delicate with patches		Meets expectation of robustness (it may fail in the near future)		Exceptional durability, no signs of failure.		1.5
	Appearance	Unacceptable presentation		Marginal presentation		Presentation is satisfactory		Presentation meets expectations		Exceptional presentation		1
	Testing/Evaluation	No testing		Marginal testing, fail to resolve simple malfunctions		Valid testing, fail to resolve multiple complex malfunctions		Expected testing, fail to resolve one complex malfunction		Fully tested		1
Documentation and Reflection	Design Analysis	No analysis		Incomplete analysis		Erroneous analysis		Complete analysis		Complete analysis with verification		2.5
	Reflection	No reflection		Marginal and unsupported reflection		Acceptable reflection that is in some way supported		Acceptable and supported reflection		Insightful and soundly supported reflection		2.5
	Computer-Aided Design and Sketches	No Drawings (CAD and sketches)		Incomplete Drawings		Drawings that somehow supported the design process		Acceptable drawings that supported the design process		Exceptional drawings that supported the design process		1
	Other Documentation	Missing Documentation		Incomplete Documentation		Acceptable Documentation		Commendable Documentation		Exceptional Documentation		2
Work	Teamwork	Unacceptable		Marginal		Acceptable		Commendable		Exceptional		
	Individual Participation	1	2	3	4	5	6	7	8	9	10	