Creating a concept inventory set of a Kinematics and Dynamics Machinery course to support lectures in a flipped classroom environment

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ABSTRACT

Dynamics of Machinery is a traditional engineering course; in fact kinematics was one of the earliest fields of study in engineering. The course relies on a strong combination of learning new theory and acquiring the skills to apply this theory through regular and repeated practice. The learning theory is traditionally applied through traditional lecture settings while the practice is commonly incorporated through homework sets, provided through a combination of book or instructor-given assignments. Additional practice could be provided through project assignments. The topic and corresponding kinematic theory is well established. The instructor’s time is often split between lecture and supporting practice through homework and projects. Given the established nature of the theory, the class could be considered for a flipped class-room model, one in which students watch a pre-recorded lecture prior to class, and then spend class time in practicing the theory through examples. One of the limitations to the flipped model is the concern that students have not fully grasped the material from the recorded lecture. This paper suggests the use of a concept quiz associated with each pre-recorded lecture as a required component to meet prior to attending the class. The concept quizzes are associated with each unit lecture and collectively should form a concept inventory for the class that defines the fundamental range of knowledge for successful students. This paper will present the format the concept quizzes and how they are used in the flipped class environment for a traditional, junior level kinematics of machinery course. The paper will present the concepts according to topics and divided among 39 lectures associated with each class. Finally, the paper will review the outcomes of this activity over a period of multiple implementations and assessment.

INTRODUCTION

Kinematics and Dynamics of Machinery (KDoM) is a traditional topic in mechanical engineering, often offered as a multi-credit hour independent course or integrated within a broader machine design curriculum. The KDOM topics are typically seen by students at the junior-level and have as prerequisites both Statics and Dynamics. The KDOM course introduces the theory of kinematics and merges it with the fundamental laws of dynamics to develop the basic skills needed to analyze and design basic mechanisms. The course covers topics for analysis and design of linkages, cams, and gears while providing a foundation for classes such as Machine Design and similar technical elective courses. KDoM topics provide a variety of opportunities to introduce programming and software tools for mechanism analysis and synthesis methods. The course is also well suited to introduce mechanism design projects.

The documentation of such mechanical concepts began during the industrial revolution with the research of Franz Reuleaux. Reuleaux published the first book on Kinematics of Machinery in 1875, and is credited for numerous fundamental concepts including “kinematic chains” [1]. KDoM courses grew from this original text, which has become the foundation for the successful KDoM classes of today. The subject has grown to
encompass robotic systems, compliant mechanisms, biomedical applications, nano-scale machines, and many more [2-7].

Although the field of KDoM has grown immensely since Reuleaux’s first publication, the methods of class room instruction including lecture, homework and assessment have remained largely the same [8]. The course is most commonly provided in a lecture format that gives a mixture of presentation of theory, review, discussion and examples, all led by the instructor. The homework assignments are given by the instructor to provide sequential practice to reinforce the lecture content and are performed outside the classroom. Depending on the instructor direction, assigned homework problems are completed independently or by groups of students.

The widespread availability of online connectivity as well as the wide range of tools and information sharing in technical topics provides a significant opportunity to impact educational experiences in engineering. One of the models proposed for this impact is the so-called flipped-classroom, a teaching experience in which the primary lecture materials are provided in a digital format to be viewed outside of the classroom, while practical problem solving (often seen in homework) is conducting inside the classroom [9]. The flipped classroom visibly flips the traditional lecture content from inside to outside of the classroom, but also shifts the classroom role of the instructor from primary lecturer to a guide of student practice through problem solving or design efforts during course time [10].

The flipped classroom experience is seeing significant use in some disciplines such as medicine and business courses, but much less in upper-level engineering courses. The emphasis on developed skills and application of engineering theory as key objectives in the engineering curriculum provides a motivation to explore new options for engineering education. The authors could not find any reference of a flipped class effort for a KDOM or similar course. The primary model for the flipped-course experience is to provide the lecture experience outside of the classroom (11). The lectures are provided in a digital recorded format and are accessed online. The lectures are sequenced to the class, with one lecture video required to be viewed by the students prior to each class. However, the recorded lecture video is often shorter than the traditional lecture period (12). This may be due to a lack of interaction with students during the traditional lecture period. During the class period, the instructor reviews any questions from the video lecture and then practices reinforcing problems from the theory contained in the corresponding lecture. This practice may or may not be the assigned homework.

One of the products associated with developing a flipped class room for KDOM is the resulting set of lectures provided online for the students. This series of lectures intended to be watched prior to the class can be used in other ways as well. Students can and often use this material as review prior to large assignments or tests. The recorded material can be used to make up for missed classes or can be used to pace a student’s access to class material, for example reviewing ahead to help with a particular design project or challenge. Alternatively, the recorded lectures provide a few limitations for the instructor. One is a lack of feedback that naturally occurs in the classroom, allowing an instructor to change pace or reinforce lecture material that may be difficult for a set of students. Traditional lecture also provides clear evidence that a student did or did not attend and sit through the lecture. These things are generally lacking from the flipped-classroom approach of recorded lectures.

One approach around this is to require students to watch the recorded lecture and take a quiz at the end of the lecture that serves as a check that they watched and achieved a basic understanding of this material. This quiz can be a basic test unique to the lecture. In general, one quiz is associated with each lecture, each quiz is simple and quick to complete, and each serves as a point to confirm that students have viewed the corresponding lecture and achieved a basic understanding. Further, it is desirable that the quizzes can be used to assess students’ fundamental understanding of course concepts. As assessment tools, students can use these quizzes to gauge their level of understanding of the course material contained in the lecture, and review and practice the lecture material until a sufficient competency is reached. When considered in this light, the quiz sets become a basic description of a concept inventory for KDOM. The idea of a concept inventory is to measure conceptual rather than computational understanding of subject material (13).

Concept inventories are generally created through collaboration members of the community, and include testing and iteration to define and refine a more complete set (15). Concept inventories around fundamental concepts in physics and Newtonian Mechanics are well developed and documented through the Force Concept Inventory (14). Here, concept inventories on topics including Dynamics, Fluid Mechanics, Heat Transfer, Strength of Materials, Thermodynamics and Materials are presented. However, concept materials for Kinematics and Dynamics of Machinery could not be readily found by this author. This work provides a very early consideration into developing a concept inventory suitable for the KDOM course for undergraduate
engineering students. The paper will present a useful motivation as part of the monitoring and assessment in a flipped-classroom experiment. Finally, the paper will present an initial set of questions for a concept inventory on some of the topics covered in KDOM and present an initial evaluation of these based on implementation over several semesters at Tennessee Tech.

CONCEPT INVENTORY FOR KDOM

Of the multiple tools proposed for evaluating student’s conceptual understanding of technical theory, concept inventories have been the most prominently studied and implemented (16). Concept inventories are a series of multiple-choice questions that focus on conceptual rather than computational aspects of course theory. The questions span the general range of theory to be covered and are contained in multiple-choice quizzes that are easily administered and taken. They can be used individually to evaluate understanding of a specific topic or across a class or multiple classes to yield statistical analysis of student learning. They can evaluate teaching approaches and help students and instructors gauge and adjust learning.

The KDOM-CI was developed using the process suggested by [18] and has been modified for the specific purpose of evaluating students’ understanding of key learning points at a series of steps throughout the semester. This process is listed as follows

- Define the overall fundamental concepts that are to be evaluated using the KDOM-CI and organize into each lecture unit
- For each lecture unit, evaluate how each student learns about the concept
- Create two to four questions for each concept
  a. Each concept question should be multiple choice
  b. Take less than two minutes to complete
  c. Be arranged in groups of five to ten
- Perform an initial testing on students, compare with other assessment measures
- Revise the question as needed

The following section will discuss how these steps were implemented in constructing the KDOM CI and present some of the early, practical details for the course and use with pre-recorded lectures.

PROCEDURE TO CREATE CONCEPT INVENTORY FOR KDOM

Step 1: Define overall concepts associated with KDOM and organize into lecture units:

The course conceptual material is defined and organized into topics as defined in Table I. This list can be subjective in order, arrangement, depth and range of inclusion by instructors, but is assumed to represent a typical range of topics (4). Within each topic, a series of concepts are selected and is further divided into the number of recorded units. For the purpose of this work, one concept quiz is organized for each recorded unit.

<table>
<thead>
<tr>
<th>Table I: KDOM concepts organized by Topic</th>
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<tbody>
<tr>
<td>Topic</td>
</tr>
<tr>
<td>Kinematics Fundamentals (2 Lectures)</td>
</tr>
<tr>
<td>Position analysis (3 Lectures)</td>
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<tr>
<td>Velocity analysis (3 Lectures)</td>
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<tr>
<td>Kinetostatics of Mechanisms (4 Lectures)</td>
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<tr>
<td>Acceleration analysis (3 Lectures)</td>
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<td>Kinetostatic analysis of Mechanisms (4 Lectures)</td>
</tr>
<tr>
<td>Linkage synthesis (4 Lectures)</td>
</tr>
<tr>
<td>Gear trains (4 Lectures)</td>
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</tbody>
</table>
Step 2: For each lecture unit evaluate how each student learns about the concept:

Students experience the material over three to five instances in the course; first through the lecture (recorded and viewed prior to class), followed by in class open discussion and practicing examples, assigned homework, examination problems and sometimes in a course design project. The design project in the author’s KDOM course is open-ended and therefore does not guarantee that any one topic is covered on the project. Given this review, the purpose of the CI (concept inventory) quiz plays different roles. The primary roles in this case are to provide a first check on conceptual understanding following the initial lecture review, provide feedback to guide in-class discussion, and potentially serve as further assessment of mastery of fundamental concepts. These considerations influence the depth and level of the CI questions. Two types of questions are thus appropriate; one set to gauge understanding after early exposure and the second to secure expected levels of concept mastery in the course.

Step 3: Create two to four questions for each concept:

Steps one and two create a list and framework for defining the CI questions. Additional criteria are defined to suit the specific objectives of association with recorded lectures are as follows;

- Each concept question should be multiple choice
- Take less than two minutes to complete
- Be arranged in groups of five to ten

Generating questions comes in part from reviewing existing sets of quiz, homework and test questions and a collaborative review with other faculty teaching the same or similar type questions. Generally, the questions are constructed by first identifying the key principles or concepts that surround each of the topics listed in Table 1. Once a principle or concept is selected, typical use cases or scenarios in which a practitioner would experience these concepts are listed, and then an example type problem is listed that represents that scenario. Typically, the scenarios are common and readily recognized by engineering students, often with preconceptions of what an answer might be. However, each question should be readily relatable to the course material and staged in a way that a proper answer is influenced by kinematic methods. Generally, the correct answer is first defined for the problem along with one or several obviously incorrect answers. The team then will try to generate one or two answers that are partially correct but still not satisfactory with complete underlying knowledge of the kinematic concept. In this case, answers can be identified as those completely correct, partially or completely incorrect.

Once the questions and answers are established in concept, they are formally constructed in an appropriate tool. For the author’s purpose, these questions are constructed in a digital quiz tool through the course management software called iLearn (Canfield et al., 2015). The questions are organized according to the lecture units. Typically it is desired to have about two questions per individual concept and no more than ten questions per quiz, with each quiz associated with a recorded lecture unit. The quizzes are expected to take no more than 10 minutes to complete.

Step 4: Perform an initial testing on students, compare with other assessment measures:

Once a unit’s questions are completed for the KDOM CI, it is initially tested on the students. Early versions of the test serve as a trial of the questions, permit corrections for simplistic mistakes in the communication with students and gauge the validity of the question in comparison with other assessment measures. The primary comparison assessment measures are homework grades and exam performance. Additionally, feedback and discussion with students about the questions lead to valuable insights. These insights and corrections are used to update and improve the KDOM addressed in step 5 below.

Step 5: Revise the questions as needed and implement:

The revision process is based on feedback from students in the early testing stage and is an ongoing process. The questions are then implemented for ongoing use in the author’s KDOM course. Questions from the KDOM CI are used to create approximately twenty quizzes, one associated with each recorded lecture for the semester-long course. Note that in this application there are 42 class sessions over a semester, with approximately half of these classes expecting preview of a lecture and completing a concept quiz. During the first half of the semester, the lectures occur routinely, while in the second half of the course more time is spent in
applications of course material with less recorded lectures. The concept quizzes are graded and included in determining the student’s grade, to ensure that they were completed and taken seriously. However, these quizzes represent a very small portion of the grade and are evaluated primarily based on timely completion and participation in the quiz process.

SAMPLES FROM THE KDOM CI QUIZZES

This section will provide examples on some of the KDOM CI quizzes. The first examples provide more discussion on the nature of their development and the author’s objective and approach in constructing the associated problem. The latter examples provide more coverage. A more complete listing of quizzes are available online at the author’s website (web address in conclusion). The goal of presenting these questions are to initiate discussion and generate improved questions that form a more formal KDOM CI with broad participation from the mechanisms and robotics community.

Example set 1 - Mobility: This first example considers three questions related to measuring fundamental concepts in mobility. The first considers a basic understanding of motion and degrees of freedom or independent motions.

The correct answer is C, with two potential ways considered for the student to arrive at the answer: two independent motions at the knuckle and one from bending the finger (assumes that bending at the middle and distal joint are coupled) or two from pointing and one from bending the finger. Question D is expected to be the second most likely answer, with some confusion expected from students that may think bending about the knuckle is independent from pointing.

This problem makes a student think about motion in multiple cardinal directions with the track as a constraint. In this question, the students must think about constraints that go beyond the simple revolute or linear prismatic bearings, but serves the same purpose to force the roller car to follow motion prescribed by the track, with the only freedom to displace along the track.

One of the issues in creating these problems are the degree of additional notes that should be added to the potential answers under consideration. The answers first must be correct or incorrect. The additional comments though are intended to align with a student’s understanding on the problem. The goal is to eliminate guessing, or solidify why they selected that answer. It is undesirable to provide misleading information or a correct answer with unexpected conceptual logic.

Example set 2 - Gear trains: The next series of questions consider another topic, gear trains. The questions suggested below provide an early assessment of fundamental understanding of involute-tooth gear systems. Note that these problems are constructed specifically to 1) avoid repetition of facts or terminology, and 2) avoid computation. However, the
The student will need to call on facts, terminology and or think about what might be used in a computation to answer these questions.

The following three examples test very simple understanding of fixed axis gears transmitting motion.

**Figure 4: Gearing Question**
Which of the following mechanisms satisfy the fundamental law of gearing?

- a) A & C
- b) B & D
- c) D only
- d) A, B & D

**Figure 5: Gearing Question**
If gear 1 is rotating at 50 RPM, then the rotation of gear 2 will be

- a) Faster and opposite direction of gear 1
- b) Slower and opposite direction of gear 1
- c) Equal and opposite direction of gear 1
- d) Equal and same direction of gear 1

**Figure 6: Gearing Question**
In the compound gear set shown, Tout will be __________ compared to Tin?

- a) The same
- b) Greater
- c) Lesser
- d) Not enough information given

The following three examples ask the students to think about implications of gear pitch and pressure angle:

**Figure 7: Gearing Question**
Consider the following gears. Which gear would be most suitable for an application that requires the smallest number of teeth?

- a) A
- b) B
- c) C
- d) A & B

**Figure 8: Gearing Question**
Consider the following gears each with 16 teeth. Order them from smallest diameter to largest.

- a) C, A, B & D
- b) B, C, D & A
- c) D, B, A & C
- d) A, D, C & B

**Example set 3: Linkage Analysis**
The last example is provided to illustrate conceptual understanding in linkage synthesis. The conceptual problem asking a student to graphically assemble links is similar to the problem of mathematically solving a loop closure problem, and in this case to think about the number of solutions that should result under different circumstances.

**Figure 9: Gearing Question**
Both gears sets shown give a 10:1 ratio. Which is more efficient?

- a) A
- b) B
- c) The have same efficiency
- d) Not enough information given

**Figure 10: Linkage Question**
Consider the collection of links, how many ways can the 2 and 3 cm links be assembled to form a four-bar?

- a) 1
- b) 2
- c) 3
- d) >3

**IMPLEMENTATION AND DISCUSSION**
The section above provided a variety of examples of problems that form the initial KDOM–CI. This effort was began in 2014 to with a more simplistic set of questions with less graphics, more reliance on pure word questions and led to a series of approximately 150 questions distributed over 25 quizzes. A transition to more conceptual questions including a scenario presented by a figure has been made and now represents the proposed model for the KDOM–CI. This led to the current KDOM–CI which has been tested with one semester of students. Some historical results of the early question format suggest that the students performed very well (averaging 85%) on these quiz formats. However, it was deemed that the questions did not go sufficiently deep to test true understanding of the concepts. The current KDOM–CI questions average a much lower correct answer average. For grading purposes, these results are scaled to emphasize primarily completion keeping the overall contribution to the grade the same as in past semesters. A goal of approximately 70% correct average representing a minimal level of understanding is selected. This is based on results seen in other CI implementations (Hestenes). This also gives students room to evaluate their learning and continue to grow.
their conceptual understanding and test this growth. The number of questions needs to grow as well in order to aid students in increased understanding. The answers are provided to the students as soon as they complete a KDOM-CI quiz. Retaking the same quiz is a less accurate measure of improved understanding, so it is desired to have two to three quizzes for each lecture topic in the future.

CONCLUSIONS
A KDOM-CI has been constructed. To the author's knowledge, this is the first such concept inventory (CI) in the Kinematics and Dynamics of Machinery course presented in the literature. The primary goal of the KDOM-CI is to help students gauge and self-regulate their learning from watching pre-recorded videos and completed assigned reading prior to in-class practice and discussion. This KDOM-CI is being implemented in a flipped-class arrangement for a junior level KDOM course in Mechanical Engineering at TTU. Students can choose between a more traditional lecture-based KDOM and the flipped-class KDOM at TTU. Early observations show that the quizzes serve their primary purpose of mandating that students perform the pre-class lecture viewing and reading in a timely fashion. The KDOM-CI is currently being assessed further to provide a stronger measure of student performance and class performance using statistical measures. Interested instructors can access the current KDOM-CI at https://www.tntech.edu/engineering/departments/me/facultyandstaff/.

REFERENCES:
12. Learning Initiative. 7 Things You should Know About Flipped Classrooms, EDUCAUSE 2012.
