TEACHING ADVANCED MODELING OF MULTIBODY MECHANISMS TO NON-TRADITIONAL ENGINEERING STUDENTS

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1. INTRODUCTION[1]

Traditional entry-level mechanics courses serve two fundamentally different objectives. On the one hand, they present a self-contained progression of problem-solving paradigms addressing particular categories of engineering situations without any specific reference to higher-level thinking or the challenges of actual systems. They provide a necessary backdrop for the further professional development of an engineering-science or mechanical-engineering student but, typically, do not generate much interest in other populations of engineering students.

On the other hand, undergraduate instruction into the subject of classical mechanics constitutes a first attempt at incorporating the mathematics taught in the undergraduate linear-algebra and calculus sequences with real-world applications, developing ideas of physical and mathematical modeling, assessing the relevance of physical phenomena, the appreciation of modeling assumptions, and the formulation of scientific inquiry. These are skills that we expect of all engineering students, but that typically are not strongly developed in existing curricula. There is a strong need for courses designed with the goal of bridging the gap between the stated objectives and current curricular realizations.

To address these issues, this paper describes a recently developed course that relies on the concept of problem-based learning to allow the student to accumulate theoretical knowledge, develop intuitive insight, and perfect a practical know-how into the modeling and visualization of complex mechanical systems and their motions. Particular emphasis is placed on a framework that appeals to the educational background, interests, and perspectives of computer-savvy students. In particular, focus is on general skills, rather than the ability to solve cooked-up problems. Active learning strategies and truly cooperative learning constitute an overwhelming part of the course design, the culmination of which is a team animation project incorporating material from throughout the course and accounting for a majority of the course grade.

This paper describes the course philosophy and educational material developed specifically for this course. This is highlighted by examples of student projects as well as some anecdotal observations from implementations at Virginia Polytechnic Institute and State University, the

[1] Parts of the material in this section have previously appeared in the preface to Dankowicz, H., 2005, *Multibody Mechanics and Visualization*, Springer Verlag, UK and appear here with kind permission of Springer Science and Business Media.

Royal Institute of Technology in Stockholm, Sweden, as well as at the University of Illinois at Urbana-Champaign.

2. CURRICULAR PARADIGM

2.1. Reduction to model

The field of multibody mechanics offers a natural environment in which to develop students' skills in abstraction and model reduction. It allows the instructor to disassociate modeling assumptions regarding the purely geometric characteristics of a mechanism from assumptions regarding mass distribution and, the more challenging, assumptions regarding physical interactions with the environment. It builds on students' naturally occurring abilities as evidenced already in the stick-figure drawings of small children.

In contrast, traditional instruction in entry-level mechanics presents a paradigm in which the confluence of the three distinct areas of abstraction dilutes their individual importance. Instead of attaining higher-level appreciation for the fundamental notions underlying abstraction and model reduction, students come away with low-level pattern-matching skills. At best, these skills enable students to address particular well-defined classes of problems with formulaic manipulation. As a result, students exhibit little understanding for the significance of the results of their analysis or alternative means of justifying their validity and probing the underlying assumptions.

It is the ability to abstract and reduce to model, to communicate the abstraction and, ultimately, to synthesize the results of an analysis based on such abstraction that underlies much of human progress. Indeed, one would argue that these abilities, while honed and perfected through nurture, are inherent and a natural characteristic of our species. At the same time, much fallacious thought may result from this innate faculty of abstraction, often harmless, but in many historical instances, quite dangerous.

It should be the aim of university engineering instruction to distill the modeling and abstraction skills of students and to put the foremost emphasis on higher-level abilities to evaluate and to justify such reductions, rather than to compute and tabulate. Second to skills of reduction should come the ability to estimate and to bracket quantitative system descriptors. Such curricular ordering would finally put the horse before the cart and properly train engineering professionals for the challenges of the future (National Academy of Engineering, 2004).

2.2. Context-driven instruction

The study of the kinematics of multibody mechanisms – the presence of geometric constraints and their influence on the available motions of the mechanism – provides an everyday context for instruction in linear algebra and differential equations. Its advantage relative to other areas of application, such as calculations of principal directions of stress or oscillations in electrical circuits, lies in the immediate ways in which multibody kinematics may be visualized or concretized and the minimum of physical intuition it demands.

The detachment present in current curricula between instruction in fundamental mathematical methods of science and engineering and topical classes within various branches of science and engineering is a lost opportunity to anchor abstraction and model reduction in a common and agreed-upon language. Indeed, as with instruction in a foreign language, it is with the integration of the atoms of speech into composite structures and contexts that learning transcends memorization. Errors of grammar and spelling become significant only when they result in failures to convey meaning. Lack of clarity is a shortcoming only when it is a detriment to communication.

As with abstraction and model reduction in the engineering sciences, there are higher-level thinking skills associated with linear algebra and differential equations that are often obscured by a myriad of computational techniques in entry-level courses. Such skills can be brought out in the multibody mechanics context, for example, by associating matrices with geometric transformations and configurational changes of physical objects. Similarly, emphasis on properties of solutions of differential equations as they relate to kinematically achievable motions of the mechanism can increase the students' affinity for the grammatical constructs underlying mathematical models of dynamical systems.

2.3. Integration of technology

The inclusion in undergraduate instruction of software tools for automation of well-defined sequences of computation, for example in eigensystem analysis of square matrices or for the solution of differential equations, is controversial and a topic that reasonable people may justifiably disagree about. On the one hand, the replacement of rote calculations by advanced, possibly symbolic, calculators is said to erode the students' understanding for the underlying notions and their ability to argue convincingly for the validity of the output from the calculator. On the other hand, it is suggested that such advanced calculators enable instruction to move beyond low-complexity problems thus lowering the bar to analysis of real-life systems and to addressing higher-level concepts pertaining to a large class of such systems.

A delicate balance between these two apparently diametrically opposite paradigms exists within engineering undergraduate education today. Where software tools are allowed in entry-level courses, they are often used only to replace routine manipulation, for example the computation of Laplace transforms and their inverses, without increasing the complexity of the problems studied or the emphasis on concepts that go beyond such manipulation. Such implementation does not advance the learning of the students beyond what would have been achieved without these tools. It supports the contention of those concerned about the inclusion of software and falls short of realizing the potential argued for by its supporters.

Naturally, the resolution to the present dichotomy lies in a paradigm that retains the desirable qualities of traditional instruction while stretching the envelope in the direction of increasingly complex incarnations of the fundamental concepts. Multibody mechanics affords an area of specialization in which such an educational paradigm can be particularly fruitful. For example, the mathematical models describing the kinematics and kinetics of individual rigid bodies may be arrived at through hand calculations with a reasonable amount of effort. Those of complicated multibody mechanisms, however, while based on the same fundamental principles are forbiddingly complicated and require computer-algebra tools for their derivation.

Similarly, while the solution of the equations of motion of particularly simple mechanisms can be obtained in closed form, this is not the case of the large majority of mechanisms. For the latter, numerical simulation and suitable use of visualization tools enable instruction to focus on the actual dynamical behavior of the mechanism and its dependence on design and external influence. In this context, it may also be useful to expose students to the development of numerical algorithms for accurate simulation of multibody dynamics, an area of active research across the world.

3. IMPLEMENTATION[2]

The observations made in the previous section have served as the impetus for the development of a course on *Multibody Mechanics and Visualization*. This course has been successfully implemented in the undergraduate curriculum at the Royal Institute of Technology (KTH) in Stockholm, Sweden and at Virginia Polytechnic Institute and State University (Virginia Tech) in Blacksburg, Virginia. The course served as a required mechanics course for approximately 600 *sophomore* computer engineers and computer scientists at KTH between 1999 and 2003. At Virginia Tech, it was offered as an engineering-science elective to approximately 65 electrical- and computer-engineering *juniors* and *seniors* in 2000-2002 and in 2004. The course material and instructional pedagogy was also implemented in a graduate-level intermediate dynamics course at Virginia Tech in 2003. Beginning in the spring semester 2006, the same course is currently offered as a mechanical engineering technical elective for seniors and as a beginning graduate-level course at the University of Illinois at Urbana-Champaign (Dankowicz, 2006).

3.1. Instructional objectives and pedagogy

The instructional objectives for this course are to prepare the students to

- Model the kinematics and dynamics of an arbitrary multi-body mechanism;
- Formulate a mathematical description of a general motion of the mechanism in terms of sets of descriptive variables and systems of differential equations governing their evolution; and
- Implement this description in a computer-graphics application for animating and visualizing a desired or observed motion of the mechanism.

In stark contrast to traditional mechanics courses, the act of analyzing a given set of differential equations to determine and predict the subsequent dynamics is entirely deemphasized. Instead, it is argued that such analysis should be the subject of a separate, subsequent course coupled with issues of design of mechanical systems for achieving desired behavior and so on. Eliminating

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such discussions from the present course enables clarity of presentation, thought, and message. It increases the likelihood that the students firmly establish the mathematical background necessary to proceed with such analysis as compared to traditional courses were the material is closely interwoven.

Four main pedagogical principles form the foundation for the course and associated courseware, namely,

- An inductive approach to learning, whereby general patterns are discerned from observations made in particular instances;
- A need for repetition and review of important concepts and their reinforcement through numerous examples;
- Visual guidance to allow the reader to differentiate between different levels of knowledge; and
- Deep incorporation of computer tools, visual representations, and elements of active learning to appeal to a broad spectrum of learning strategies and preferences.

The primary goal in composing the course text has been to provide an extensive resource that presents a self-contained and careful exposition of all relevant topics for the sequential reader while containing enough repetition and examples to allow numerous points of entry.

Not surprisingly, a particular appeal of the course is the emphasis on the creation of artistically innovative, yet mechanically and physically correct, visualizations of the motion of complex multibody mechanisms, as would, for example, appear in computer games or other virtual environments. Here, in a sense, the chosen method of assessing student outcome 'tricks' the students into learning something very useful and challenging in the pursuit of self-expression and personal pride!

3.2. Courseware

Through student feedback, course evaluations, and input from colleagues at KTH, the courseware has undergone several stages of revision. The course text which began as a 70-page compendium has reached its final size (~500 pages) with the inclusion of approximately 200 solved and unsolved exercises, approximately 200 figures and illustrations, and several completely worked-through simulation and animation projects. The textbook was published by Springer Verlag, UK, in August 2004 (Dankowicz, 2005).

Two associated software packages, MAMBO and the MAMBO toolbox have both proven their value in instruction (and research!) and have reached a stage of code maturity. They are extensively documented in the textbook and on a dedicated website (Dankowicz, 2004), from which the executables can be downloaded at no cost. This website contains tutorials on the use of both packages, as well as a database of MAMBO projects illustrating material in the text. In addition, selected student projects are continually uploaded to this site.

The Windows-based simulation and animation application MAMBO has been developed with the purpose of allowing the student to visualize the results of their efforts while retaining the need for careful mathematical analysis. In contrast with existing commercially available educational software tools, MAMBO requires detailed input from the user both in order to define the specific geometry of the mechanism as well as the differential equations governing its behavior. The computer-algebra package, the MAMBO toolbox, enables the students to provide these specifications for mechanisms that would pose insurmountable algebraic challenges to hand calculations. With these tools, the student is able to see the implications of decisions made throughout the modeling stage, to check the mathematical analysis, and to build their intuition.

Whereas MAMBO is a stand-alone application, the MAMBO toolbox is a package of computer-algebra procedures for MAPLE (or MATLAB with the Extended Symbolic Toolbox) or MATHEMATICA. No extensive familiarity with either one of these software environments is necessary to use the MAMBO toolbox, although such experience may be used to one's advantage in extending the capabilities of the MAMBO toolbox.

3.3. Student perceptions and outcomes

In assessing the validity of the approach and the effectiveness of the instruction, it was early decided that the determining factors were student perception of material, student perception of course deliverables, and student performance vis-à-vis traditional engineering mechanics courses. As the course challenged students at a significantly higher level than courses focused more on the algebra of mechanics, it was recognized that possible student dissatisfaction during the course should be weighed against possible satisfaction at the end of the course.

The results of student surveys and assessments of student performance performed at KTH and at Virginia Tech have shown that although students are uncomfortable with the expectations and freedom of a project-based course, they generally put in the extra time required to generate a satisfactory deliverable. As a result, and in spite of the sustained level of difficulty of the course, the percentage of students making a C or above was near 90% in this course as compared to 60% in the traditional mechanics courses taught at KTH. Also, many students expressed an interest in being given further instruction in the simulation and visualization of multibody dynamics including flexible bodies, although such courses have yet to be offered.

Further anecdotal evidence supporting the long-term impact of this course on students' retention of material and career choices is provided in correspondence with a select number of Virginia Tech graduates several years after graduation. For example, one student chose to pursue a graduate degree in graphics and animation indicating that "the course is one of the foremost classes to have truly impacted my school career, for its uniqueness and for that I learned from it" (Hanisch, 2003). Another student expressed "I couldn't believe how useful this class could be in the real world" (Shin, 2004).

4. SAMPLE PROJECTS

As indicated above, a majority of the course grade and assessment of student performance in this course is based on individual and team animation projects of the motion of complex multibody mechanisms. In particular, where the individual project would be of typically lesser complexity and only accounting for kinematical constraints on available motions, the team projects would often involve multiple interacting multibody mechanisms, the onset and termination of individual constraints, and some limited degree of dynamics (in the undergraduate iterations primarily single-rigid body, whereas the graduate iteration includes multiple-rigid body dynamics).

In recent iterations, projects have been based on United States patents available through the patent office website (http://www.uspto.gov), for example, a scissor jack assembly with a double-lead Acme threaded screw (Garceau, 2003), a set of multipurpose locking pliers (Rivera, 2004), and a collapsible three-wheeled child stroller (O'Shea and Ayre, 2003). Here, care has been taken to ensure that the patented mechanisms included critical elements constraining the available motions and demanding the integration of the full complement of theoretical material presented in the course.

As an example of an individual student project, Figure 1 shows an implementation in MAMBO by a Virginia Tech student of the scissor jack assembly described in US Patent #6,607,181 (Garceau, 2003). Here, the design of the linkage and the presence of the threaded screw constrain the available changes in configuration to those for which changes in the orientation of the screw result in the up-and-down motion of the upper bracket relative to the lower bracket.

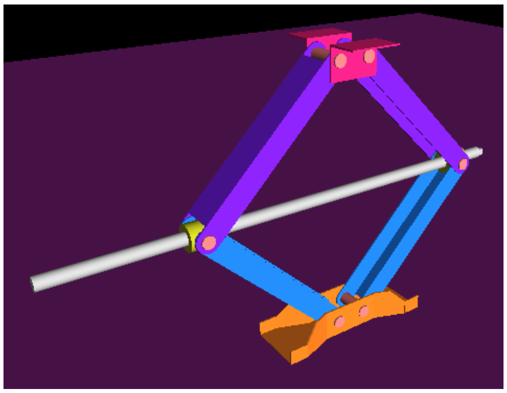

Figure 1: A scissor jack assembly implemented in MAMBO by Virginia Tech student Nefaur Khandker following US Patent #6,607,181 (Garceau, 2003).

Similarly, Figure 2 shows an implementation in MAMBO by a Virginia Tech student of the collapsible umbrella described in US Patent #6,202,661 (Okuda, 2001). Here, the design of the linkage constrains the available changes in configuration to those for which changes in the position of the sliding member results in the opening-and-closing motion of the individual frame members relative to the handle.

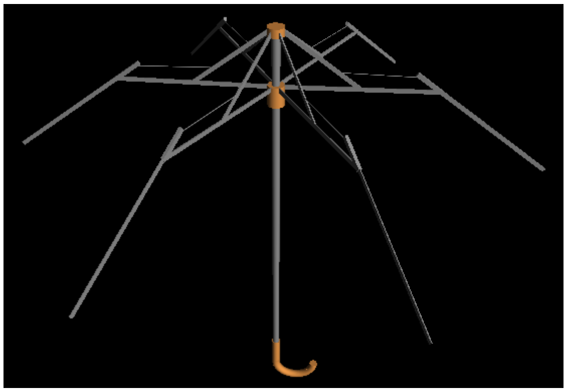

Figure 2: A collapsible umbrella assembly implemented in MAMBO by Virginia Tech student Andrew Gilbertson following US Patent #6,202,661 (Okuda, 2001).

Finally, Figure 3 shows a snapshot of the walking motion of a six-legged forest harvester developed by PlusTech OY, a John Deere subsidiary, and described in US Patent #6,109,378 implemented in MAMBO by a team of Virginia Tech students (Paakkunainen, 2000). Here, the onset and termination of ground contact of the legs of the mechanism requires a mathematical description that captures multiple parallel choices of descriptive variables and associated differential equations.

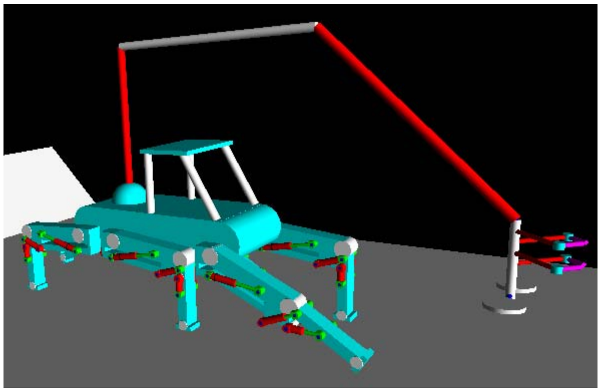

Figure 3: A six-legged forest machine implemented in MAMBO by Virginia Tech students David Hogarty, Jonathan Lee, and Brent Smith following US Patent #6,109,378 (Paakkunainen, 2000).

5. CONCLUSIONS

This paper has emphasized an instructional and learning paradigm that takes advantage of technology, of existing strengths in current curricula, and of students' desire for self-expression to impart fundamental skills in model reduction and abstraction and in critical thinking as they apply to the engineering sciences. Multibody mechanics was chosen as the vehicle for such a paradigm, due to its visual immediacy, its intimate connection to higher-level concepts from linear algebra and differential equations, and its practical use.

The realization of this paradigm in a specific course environment has been achieved at all stages of the undergraduate curriculum as well as in beginning graduate-level instruction. Indeed, implementations at KTH and Virginia Tech at the undergraduate level were targeted at students with no prior exposure to mechanics. Due to its academic calendar, at KTH, the entire course material was disseminated over a two-month period, which although stressful did not prevent the students from achieving the most spectacular results.

In parallel with the pedagogical benefits argued for above, the course also brings programmatic benefits as detailed through the ABET Criterion 3 (Felder and Brent, 2003). Its formulation addresses the need to provide students with

- "An ability to apply knowledge of mathematics, science, and engineering," [3a];
- "An ability to design a system, component, or process to meet desired needs," [3c];
- "An ability to function on multidisciplinary teams," [3d];
- "An ability to identify, formulate, and solve engineering problems," [3e];
- "An ability to communicate effectively," [3g];
- "A recognition of the need for and an ability to engage in lifelong learning," [3i]; and
- "An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice," [3k].

Properly embedded into a coherent curriculum, it further provides an interface to existing CAD courses and establishes a template for visual dissemination that finds use, for example, in capstone, senior-design projects.

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