Numerical Simulation as in Integral Component of Dynamics Problem Solving

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Abstract

The Roger Williams University faculty is committed to training students to use modern computer-based tools when performing engineering analysis. But achieving this is a tall order, as engineering courses are already jam-packed with essential technical material and any hindrance to delivering this material is unwelcome. Likewise, as faculty we routinely pay lip service to the necessity for students to double-check their work, yet we provide students with few tools for systematically accomplishing this. This paper describes an effort by the author to integrate solid modeling into a dynamics course by requiring numerical validation to symbolic homework problem solutions. The students solve traditional homework problems using free-body diagrams, equations of motion, pencils and calculators; but then must demonstrate that their answers are valid through an independent check. Students construct solid models in SolidWorks to duplicate the geometric and inertial properties of the problem, and then use the Motion Analysis add-in to create a motion study duplicating the conditions of the problem. Students may place dynamically updating dimensions to determine distances or may generate graphs, e.g. velocity versus time, to study motion. As a direct result, students are able to independently validate their symbolic solutions with numerical simulations. This paper will provide a detailed description of the use of SolidWorks in a sophomore level Dynamics course offered Fall 2010 and Spring 2011. This paper will present symbolic and numeric examples of student work and assess the benefits and problems associated with this teaching method.

Introduction

The faculty in our engineering program is committed to achieving ABET objective *k. an ability to use the techniques, skills and modern engineering tools necessary for engineering practice*. However, an isolated, introductory Computer Applications for Engineering course in the freshman year does not alone achieve this educational objective. We believe *objective k* is only achieved by four-year vertical integration of computer applications as engineering tools. But in practice this is a tall order, as engineering courses are already packed with essential technical material and any hindrance to delivering this material is unwelcome. The classical mechanics course (Dynamics) described in this paper is an effort to satisfy the two conflicting goals of building computer skills while maintaining content. Other authors have described [1,2] the challenges of achieving this objective.

Integrating computer use into classical mechanics courses is not new, as many instructors use some form of computer-aided simulation of problems [3] and some further employ problem solving software and interactive computing [4,5,6,7,8]. Dynamics is a required course for all students in the fourth semester of our eight-semester general engineering program. This course is offered to the entire sophomore class in two sections with a population between 15 and 20 students each. Because of the unavailability of a control group, statistical comparisons are of dubious value with this small sample size. Graded performance may be compared from year-to-year, but in each academic year all students receive the same course delivery.

In prior reports [9,10], I described my efforts to completely transform this course into a computer-based learning experience where problems and even class notes were taken on the computer, similar to a course described in [11]. The central vehicle to this effort was MathCAD; a computer aided engineering application that allowed for symbolic manipulation and numeric simulation. It is probable that this transformation would have continued had the developers not broken the product with their release of Version 14. The transmogrification of MathCAD caused me to abandon its use and return to a traditional chalkboard classroom in the Spring 2009 offering. This paper will discuss the effort to return some computer simulation to the Dynamics course in the form of numerical simulation of homework problems using SolidWorks.

Benefits

The Dynamics course has returned to a traditional lecture format in which I perform live demonstrations, derive relevant formulas and work example problems in chalk. Students complete weekly homework sets in groups, with each group assigned five to six problems. The problems are relatively challenging and students can expect to spend five to seven hours weekly completing the homework assignments. Each student in the homework group is responsible for completing three "initial solutions" and one "numeric check". The "initial solutions" are traditional paper-and-pencil solutions of the assigned homework problems using the student's hand-held calculator to perform computations. There is little novelty in the initial solutions; student work resembles student work of ten years ago and even resembles the homework I submitted as an undergraduate student quite a few years before that.

The novelty is exhibited in the "numeric checks", a new addition to the 2010 and 2011 classes. In these, students must construct simulations of homework problems in SolidWorks by constructing solid models duplicating the kinematic and dynamic conditions of the homework problem. Students must then use this model to check the answers of their peers, or their own work if they are working solo. The following paragraphs describe the primary benefits of this activity to student learning.

Kinematic Visualization

As a two-dimensional pictorial description is brought to life by the student's own hand; these assemblies are immediately useful for visualization. Simply by dragging the mouse, the student witnesses the motions, as gears spin, links move, bodies come into contact and range of motion limits are reached. This is particularly useful in complex kinematic problems as shown in Figure 1. Students traditionally struggle with visualizing the motion of the planetary gear system, and often incorrectly apply the relations for gears rotating about fixed axes to this problem (also shown in Figure 1). The reader may note that despite the relatively high quality graphics of the textbook image[12], the motion is still difficult to envision.

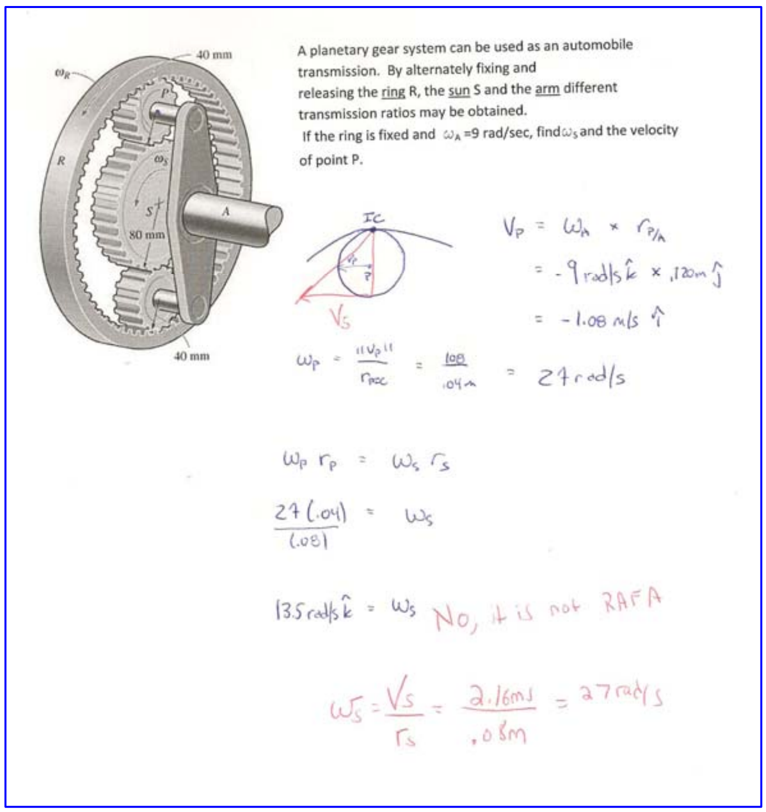
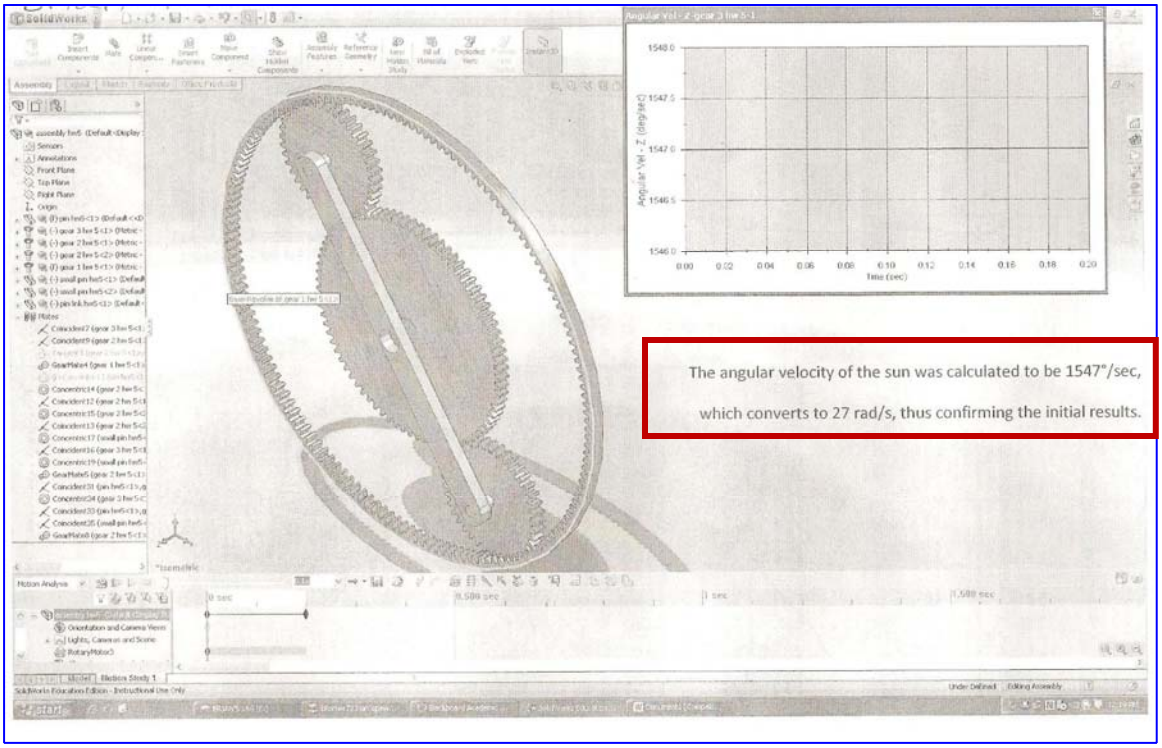


Figure 1 Complex kinematic problem, in this example, student incorrectly applied fixed-axis rotation relations.

Figure 2 shows the same problem constructed by a different student in SolidWorks. Gears are easily created in SolidWorks using a Toolbox feature that allows the user to specify the gear module in SI units (the dp in US units) and the number of teeth. By grabbing any part of the mechanism with the mouse the student may move the mechanism on the screen and observe that the planet gear is processing around the sun gear.

A stronger benefit is realized through the process of constructing the mechanism. Creating individual components is relatively easy in SolidWorks, for example, the Sun, Ring, two Planets and Arm in Figure 2 required an average of 30 minutes to build. The greater challenge is assembling the system through the process of creating "Mates" in SolidWorks. Students build individual parts as separate files and then combine these into an assembly though a series of *mates* that constrain the motion of constituent parts. For example, a student will construct a small cylindrical pin and place this in the assembly as a fixed object. Next the student inserts a gear part and constrains a central bore hole on the gear to be concentric to the central axis of the fixed pin. Next, students will constrain the front face of the pin to be flush with the front face of the gear. Following these relatively brief steps the gear will turn around the fixed pin when grabbed with the mouse

Figure 2 The same problem as Figure 1 constructed in SolidWorks.



An important mate for this course is the "gear mate" used to constrain two cylindrical objects to rotate about their respective axes in relative proportion. When thus mated, the teeth fluidly interweave as they move so the assembly appears to work as expected. (However, the program is not simulating tooth-to-tooth contact; it is merely rotating one shaft in proportion to the other.) The process of mating is more challenging, often requiring two hours, as students think carefully about how each component moves in relation to the others. In this example, students routinely create a gear mate between the ring and the planet gear, but then observe the mechanism "does not move right", meaning they observe teeth passing through each other or that they cannot move the arm with the mouse.

Students are organically learning that the planet gear is not rotating in relation to the ring. The ring gear is fixed, so a gear mate would require the planet to remain fixed. Rather the planet is experiencing general plane motion rolling along the inside of the ring. Figure 3 shows the same problem solved by the group partner of the student shown in Figure 2. This solution employs the correct methodology and finds the velocity of center of the planet gear using the instantaneous center touching the ring gear.

Motion Studies

Once the basic kinematics are established, student move to the *Motion Study*, a rich set of SolidWorks features allowing students to analyze motion. Figure 4 shows a student submission of a motion study implementing the problem shown in the inset. The controls for the Motion Study can be seen at the bottom on the panel. SolidWorks displays a timeline and above it (boxed - Figure 4) a horizontal band of controls for creating motion. In this problem, students place a linear motor of constant speed on the block moving to the left. Then the student creates a motion plot selecting to display the angular velocity of arm AB about the z axis. The velocity is changing with time, so the student places appropriate dimensions on the assembly and moves the time pointer to the moment when the angles are equal to the given problem. A vertical line shows the equivalent instant in time on the graph and the student may read the angular velocity directly from the y-axis. SolidWorks provides a full set of controls for motion studies, including the ability to impose arbitrary velocities or acceleration in any direction. Multiple motors may correspond to different degrees of freedom, and motion in one degree of freedom may be a function of another degree of freedom.

Although the examples in this paper describe kinematics, SolidWorks also provides kinetic tools. It is possible to apply forces and/or moments, activate or deactivate gravity, specify contact stiffness and specify coefficient of friction. There is a slight work-around as many book problems specify the dimensions of a body and give its mass. Although it is possible to explicitly set the mass of a body, this is problematic for calculating the moment of inertia. A work around is to create the body at the specified dimensions and evaluate the volume of the body. Then create a custom material with the density necessary to give the body the specified mass.

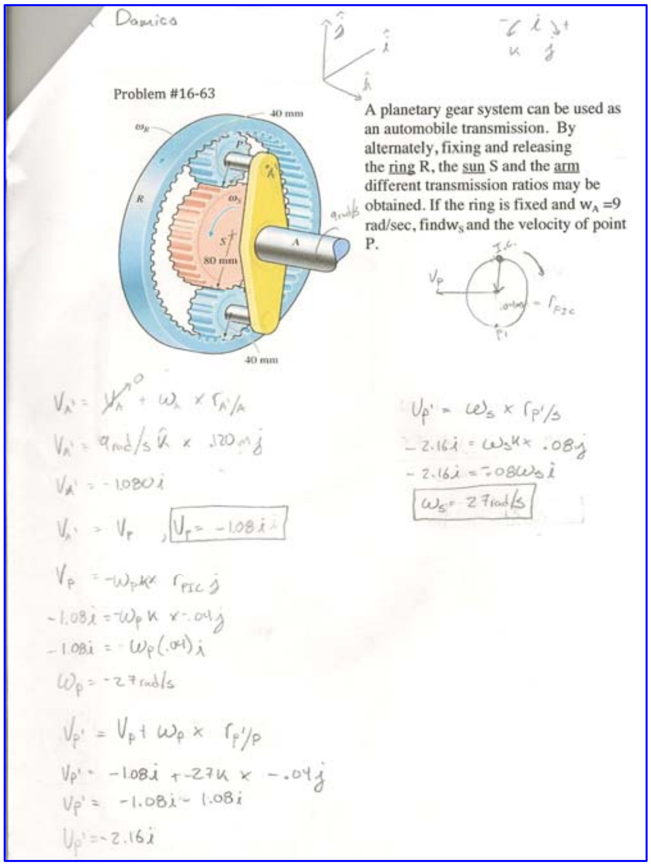


Figure 3 Problem solved again after checking SolidWorks motion.

Note that the advanced motion analysis features are available in the "Motion Analysis" mode of the "Motion Study", both highlighted by boxes in Figure 6. The "Motion Analysis" option is only available using the Motion Analysis add-in to the SolidWorks application and this option is not included with the free student version of the software.

Back of the book answers?

Although as faculty we may debate the wisdom of providing "back-of-the-book" answers to homework problems, we would probably agree that back-of-book answers are rarely available in engineering practice. Rather, successful engineers have developed the skill set necessary to check their own work through various techniques. We claim a portion of this class satisfies ABET objective *i. a recognition of the need for, and an ability to engage in lifelong learning* due to the training our students receive developing techniques to check their own answers.

Each group is required to develop a numerical simulation that checks the work of the other students in the group. To do this, the student must construct a model of the problem and then use the motion study tools to duplicate the given conditions of the problem. As shown in Figure 5, students have simulated the motion from the textbook problem and stopped the simulation at the specified instant in time. Students do not simply report the velocity they find, but compare it to the symbolically calculated velocity. As demonstrated by the block of text added by the student to the bottom of the screen shot, the measure of success is how convinced the students are that their answer is correct.

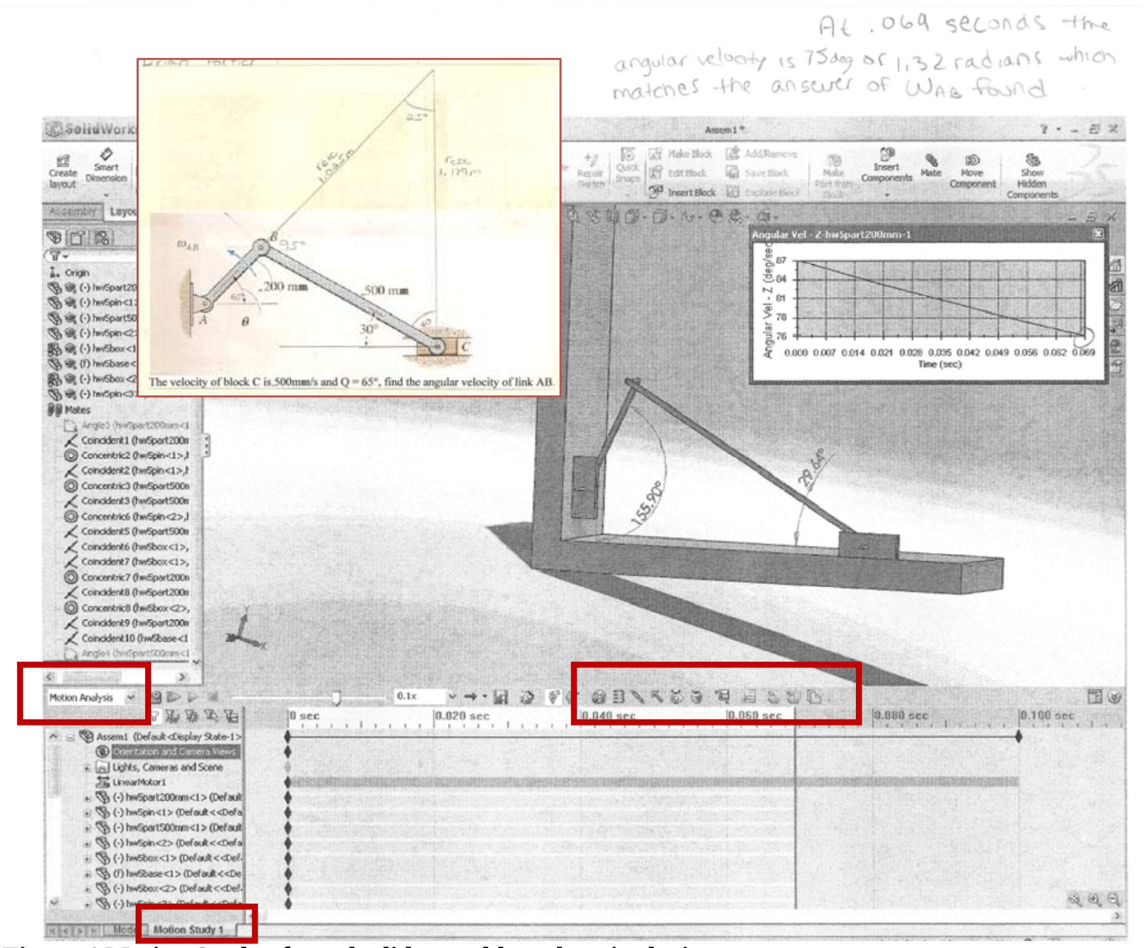
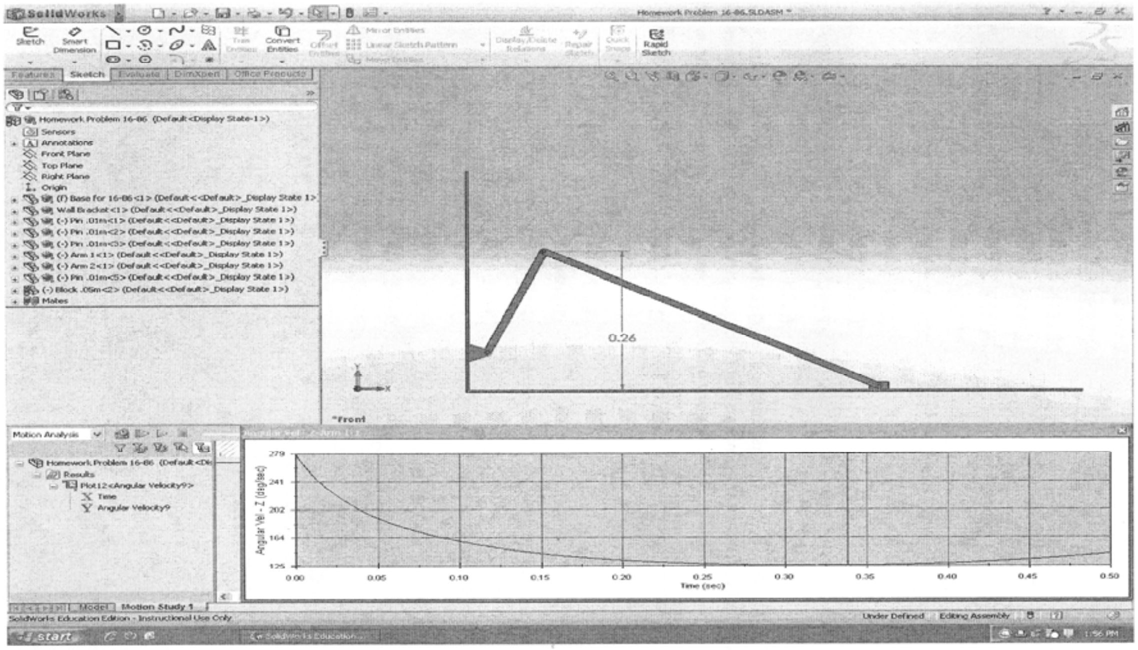


Figure 4 Motion Study of crank-slider problem show in the insert.

The understanding that engineers must devise means of teaching themselves is critical to an ABET accredited program, yet it is not clear that traditional homework assignments are effective at teaching it. The numeric simulation is an alternative means of producing an answer, and neither symbolic solution nor numerical solutions is as convincing in isolation as when the two methods produce the same result. Students recognize the potential of the simulation to produce erroneous results and often initially produce completely different results than they calculate. There is a subtle moment students experience when they can find nothing else wrong with their simulation and start to believe that the error must be in their calculation. Other than checking back-of-book answers, these students have never had the capability to prove themselves right before, and they find this experience exhilarating.

A final benefit is exercising and enhancing our student's skills in SolidWorks. Our students learn SolidWorks in a three-credit "Engineering Graphics and Design" course in their first semester. The Dynamics course is in the fourth semester, and even by this point they have become a little rusty. If we do not require students to use SolidWorks as an integral part of their intermediate coursework we should show little surprise when they show up as seniors having forgotten it all.



This Numeric check for problem #16-86 proves that the solution obtained by using the method of instantaneous centers was correct. In this solid works solution a motor was attached to the block in the negative x direction. The red bar on the graph is placed at .34s so that the orientation of the model in solid works mirrors that of the problem on paper. The graph shows the angular velocity of the arm AB (the arm closest to the wall) which is roughly 125 degrees/s. When converting to rad/s we get 2.182rad/s. Our calculated result was 2.173 rad/s giving us an error of .4% which can be accounted for in the rough estimate of the reading of the graph. NOW ISN'T THAT CONVINCING!!!

Results

The use of SolidWorks to check problem answers was first instituted in Fall 2010, and is currently underway in the Spring 2011 class. The course critique document asked students to anonymously respond to the question:

> *This is the first year I asked for numeric confirmation of answers using SolidWorks. You are welcome to make general comments and/or observations on the idea of applying SolidWorks to the Dynamics course.*

Of the 30 students that responded, 20 indicated that they were enthusiastic about the idea but 10 had misgivings. Below are representative comments in roughly the proportion that similar sentiments appeared in the responses.

I think it is amazing when one gets the same answer in solid works and in equations when solving a problem but sometimes it makes it very hard to get the answers to work, it sometimes makes it irritating.
I think it was relatively helpful - it allowed us to really visulize how these problems worked.
I like Solidworks, but there are often problems with Solidworks working for the specific application needed. It is not always a valid check because sometimes you can get the correct answer by changing numbers (i.e. densities, weights, coefficients of friction) in order to attain the answer the initial solution obtained, whether the answer is correct or not.

The student who authored the third comment included above refers to one of the caveats of this approach. As student's skills develop in SolidWorks motion analysis they also develop sufficient skill to fake their results. They recognize that they can produce almost any desired result by tweaking input parameters such as masses, lengths and angles. Although this is an important lesson to learn about numerical simulations in general, the intent was for them to use the tool to find errors in their calculation, not to tweak results to match their errors.

Conclusions

This semester I have made some adjustments that I anticipate will make the use of SolidWorks more beneficial. I introduced SolidWorks earlier in the course, even for rectilinear motion problems. Although the simulation is little more than boxes representing cars moving in straight lines, time varying acceleration made the problems sufficiently complex that it was worthwhile to see what the simulation produced. The prior semester was a heterogeneous mix with some students having no prior experience in SolidWorks. The Spring 2011 cadre of students was taught SolidWorks in their freshman year, three semesters before the current course.

Outcomes of this innovation will be measurable in two ways. The first will be measured by performance on class examinations. Does this homework system produce students that perform better on final examinations? The second outcome will be measurable downstream. Will this cadre of students automatically turn to simulation in general or SolidWorks in particular to validate their deign assumptions? This question will be investigated in future publications.

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