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NUMERICAL SIMULATION AS IN INTEGRAL COMPONENT OF DYNAMICS PROBLEM SOLVING

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ABSTRACT

The engineering faculty at Roger Williams University are 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, 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 of symbolic solutions to homework problems. 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, a SolidWorks Simulation 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 characteristics. 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 spring 2012 and spring 2013. This paper will present examples of student work and assess the benefits and challenges associated with this teaching method.

INTRODUCTION

The faculty in our engineering program are 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 this challenging in practice, as engineering courses are already packed with essential technical material and any encumbrance 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 skills while maintaining content. Other authors [i,ii] have described the challenges of achieving this objective.

The literature shows that many instructors use some form of computer-aided simulation of problems [iii] and some further employ problem solving software and interactive computing [iv,v,vi,vii,viii]. *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 of thirty students each.

In prior reports [ix,x], I described my efforts to completely transform this course into a computer-based learning experience where problems and even class notes were taken via computer, similar to a course described in [xi]. The central vehicle to this effort was MathCAD; a computer aided engineering application that allowed for symbolic manipulation and numeric simulation. The transmogrification of MathCAD in its Version 14 release caused me to abandon its use and return to a traditional chalkboard classroom in spring 2009. Frustrated, but committed to pursuing this objective, I began to employ SolidWorks motion studies in 2009 as a numerical tool to compliment theoretical problem solving. In the subsequent years I developed and enhanced the incorporation of SolidWorks so that it is now an essential and effective component of the course.

CHALLENGES

The primary challenge to this approach is building student competency in SolidWorks. There is scarcely enough time in the course for engineering mechanics content, leaving no class time for SolidWorks training. The engineering program incorporates an *Engineering Graphics and Design* course in the first semester provides sufficient prerequisite skills in SolidWorks for the majority of the population. *Dynamics*, offered in the fourth semester, must overcome gaps in preparation that have opened due to the passing of time from the first to fourth semester and for transfer students without prior experience in SolidWorks.

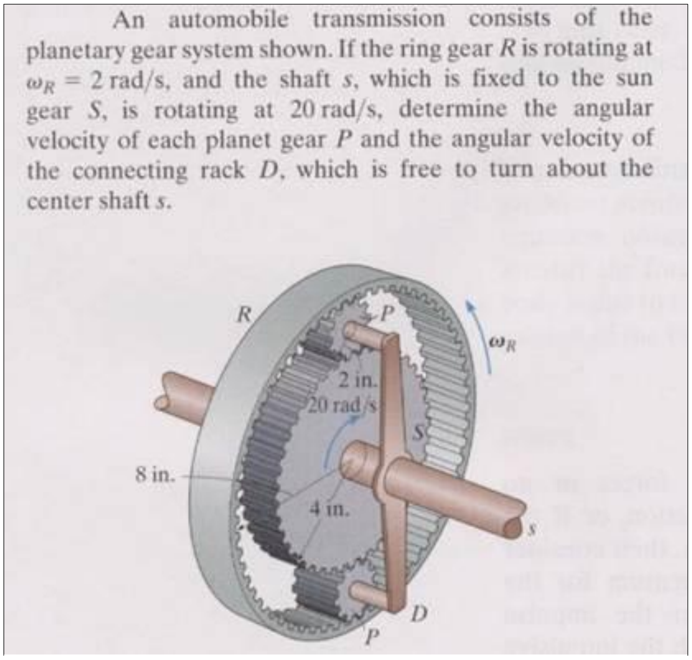

FIGURE 1 PLANETARY GEAR TRAIN HOMEWORK PROBELM

To provide instructional support without dedicating valuable class time, I created a library of narrated video demonstrations. Each video guides the viewer keystroke-by-keystroke through the SolidWorks application to create a SolidWorks simulation of each of the forty-three in-class example problems. The simulation must duplicate the mechanical conditions of the problem and produce a numerical result for an output parameter. This result is compared to theoretical analysis with algebraic manipulation of equations and computation on a hand-held calculator. Each video demonstrates how to extract numerical results from the simulation and compares these to hand-calculated results, finding remarkable agreement. Students follow the videos in the school's computer laboratory listening to the audio on individual headphones. They are often seen repeatedly rewinding and replaying the video while simultaneously constructing a simulation of their own similar but distinct homework problems. To define this term, the problems are similar in that both are, for example, projectile motion problems, but the figures, parameters and unknowns are distinct.

BENEFITS

The Dynamics course is a traditional lecture format in which I perform live demonstrations with mechanical props, derive relevant formulas and work example problems on a chalkboard. Students complete weekly homework sets in groups, with each group assigned five to six problems. As the example in Figure 1 shows, the problems, are relatively challenging; requiring five to seven hours weekly. 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", where students must simulate homework problems in SolidWorks by constructing solid models duplicating the kinematic and dynamic conditions of the problem. Students must then use this model to check their own work or the answers of their peers. The following paragraphs describe the primary benefits of this activity to student learning.

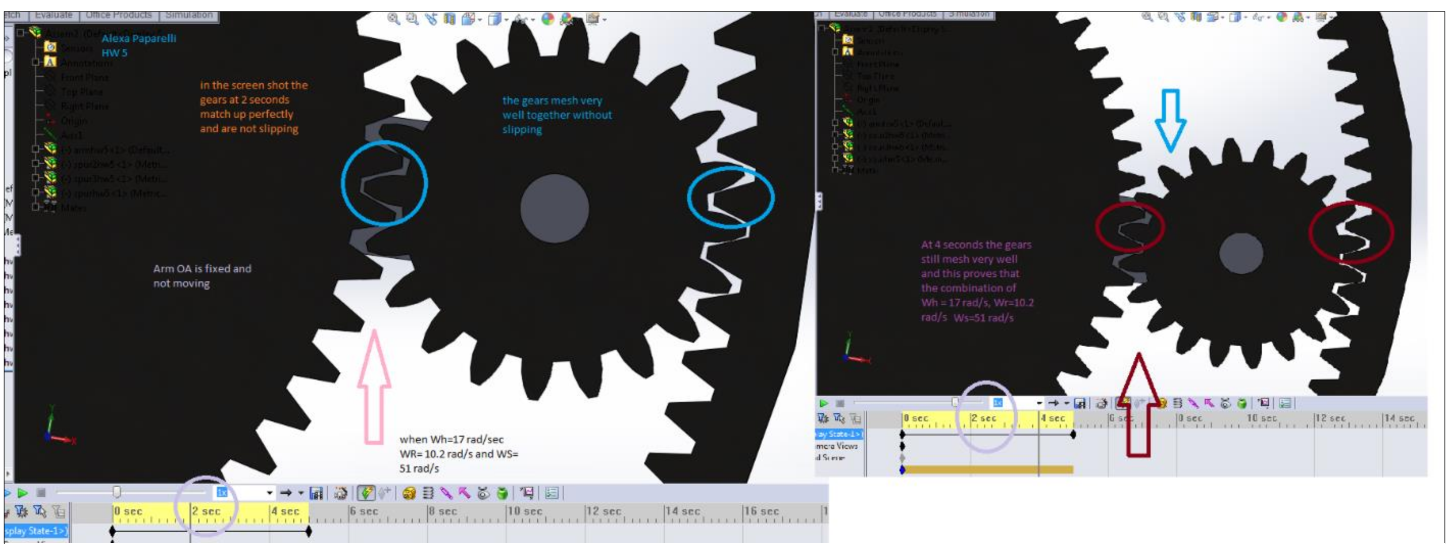

FIGURE 2 PLANETARY GEAR IMPLEMENTED IN SOLIDWORKS

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. 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 often struggle with visualizing the motion of the planetary gear system. The simulation shown in Figure 2 requires several hours to build, and in the process students must select the appropriate kinematic mate to implement the motion. Selection of the wrong mate either causes a simulation error or the gear teeth to pass through each other during simulation. A properly built gear system will be pleasing to watch as gears enmesh and planet gears revolve around the sun gear. I expected that this would in itself be gratifying and educational for the students.

MOTION STUDIES

Once the problem kinematics are established, students move to the *Motion Study*, a rich set of SolidWorks features allowing students to generate motion and analyze the results. Figure 3 shows a student submission of a motion study implementing a multiple pulley problem shown in Figure 4. The inset graphs on Figure 3 are the results of a motion study selected by the student to demonstrate agreement with theoretical results produced by integrating angular acceleration twice with respect to time. In this case, the student has selected two graphs to ascertain "how far has wheel B spun when it stops". A student may not immediately recognize that a body with a positive initial velocity but increasingly negative acceleration will eventually stop, but the motion study shows convincingly that this is the case. The student has selected to show the angular displacement versus time and the angular velocity versus time plots. The student found the time that the velocity crosses zero as the red vertical line on both graphs and reads the angular displacement at that time.

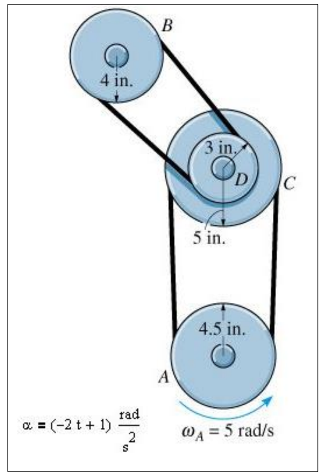

FIGURE 3 PULLEY PROBLEM

BACK OF THE BOOK ANSWERS?

Although we may debate the wisdom of providing "back-of-the-book" answers to homework problems, we would likely agree that back-of-book answers are rarely available in engineering practice. Rather, successful engineers have developed the skill set necessary to employ various techniques to check their own work. In ABET documents we claim a portion of this class satisfies ABET objective *i. a recognition of the need*

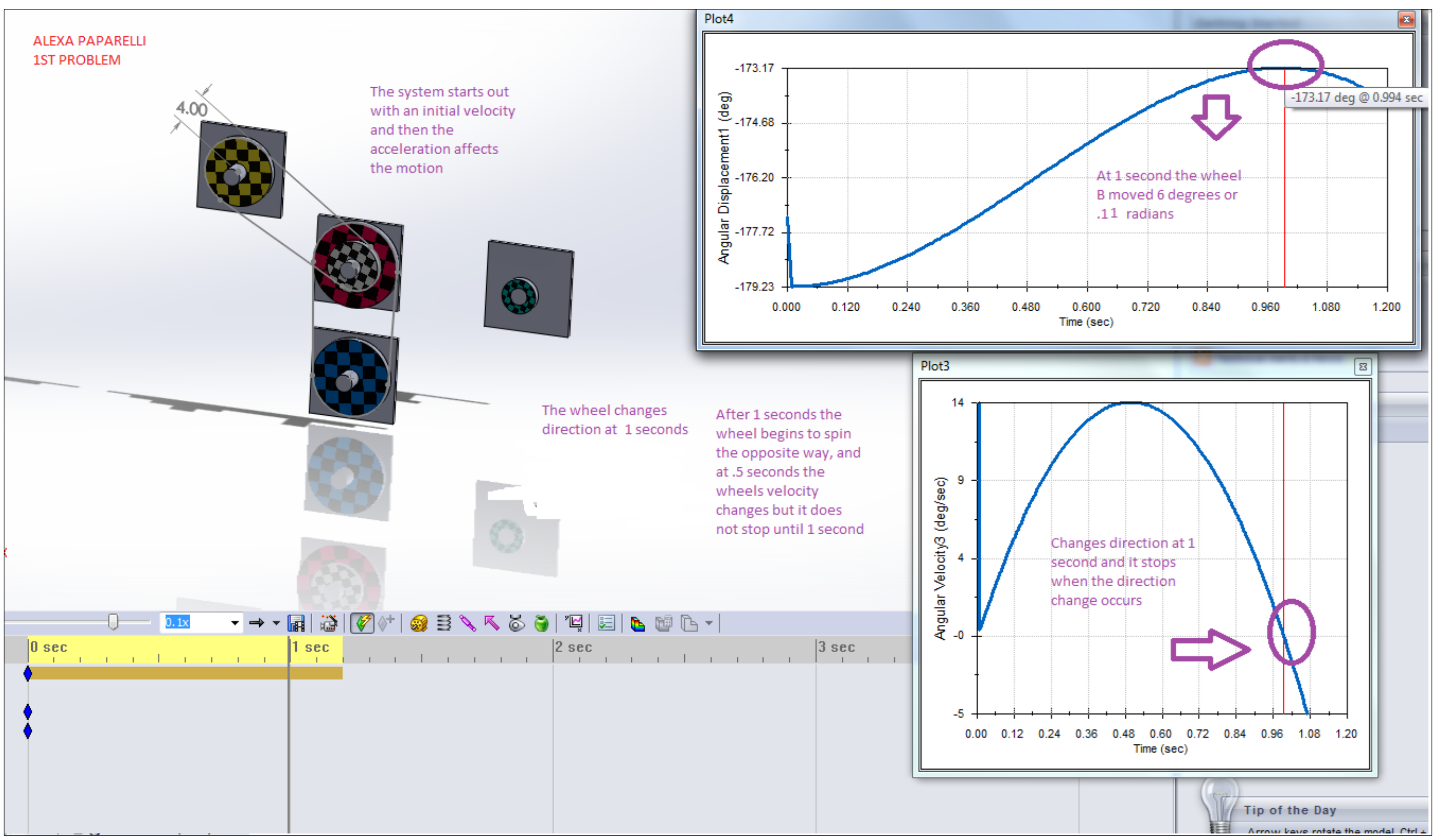

FIGURE 4 MULTI-PULLEY PROBLEM CONSTRUCTED IN SOLDWORKS

for, and an ability to engage in lifelong learning due to this training.

Each group is required to develop a numerical simulation that checks the work of the other students in the group. As shown in Figure 5, a student has simulated the motion from the textbook problem and stopped the simulation at the specified instant in time. Also seen in Figure 5 is a block of text added by the student stating "Tip velocity when bar was horizontal was 172in/s which is 14.25ft/s. Calculated value was 14.32ft/s." Note that Figure 5 is a kinetic simulation of the rod falling under the effect of gravity, whereas the previous figures demonstrated only kinematic simulation.

Training engineers to devise their own means of teaching themselves is critical to an ABET accredited program, yet it is not clear that traditional homework assignments effectively produce this outcome. The numeric simulation is an alternative means of producing an answer, and neither the symbolic solution nor the numerical solution 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 that students experience when they can find nothing else wrong with their simulation and start to believe that the error must be in their calculations. These students have never had the capability to prove themselves right, and I expected they would find this experience exhilarating.

SKILLS

A final benefit is exercising and enhancing our student's skills in SolidWorks. We expect our seniors to use SolidWorks extensively in our capstone senior design, but our students learn SolidWorks formally in their first semester. By the fourth semester *Dynamics* course they have already 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 proclaim that they have forgotten it all as seniors.

RESULTS

The four benefits described above are simply conjectured by the author. A survey was administered to students having just completed the *Dynamics* course in the spring of 2013. The survey was (inexpertly) designed by myself to test the above conjectures by directly inquiry. Figure 6 presents data from an anonymous survey administered to students at the end of the semester. Of sixty-three students registered, fifty-eight

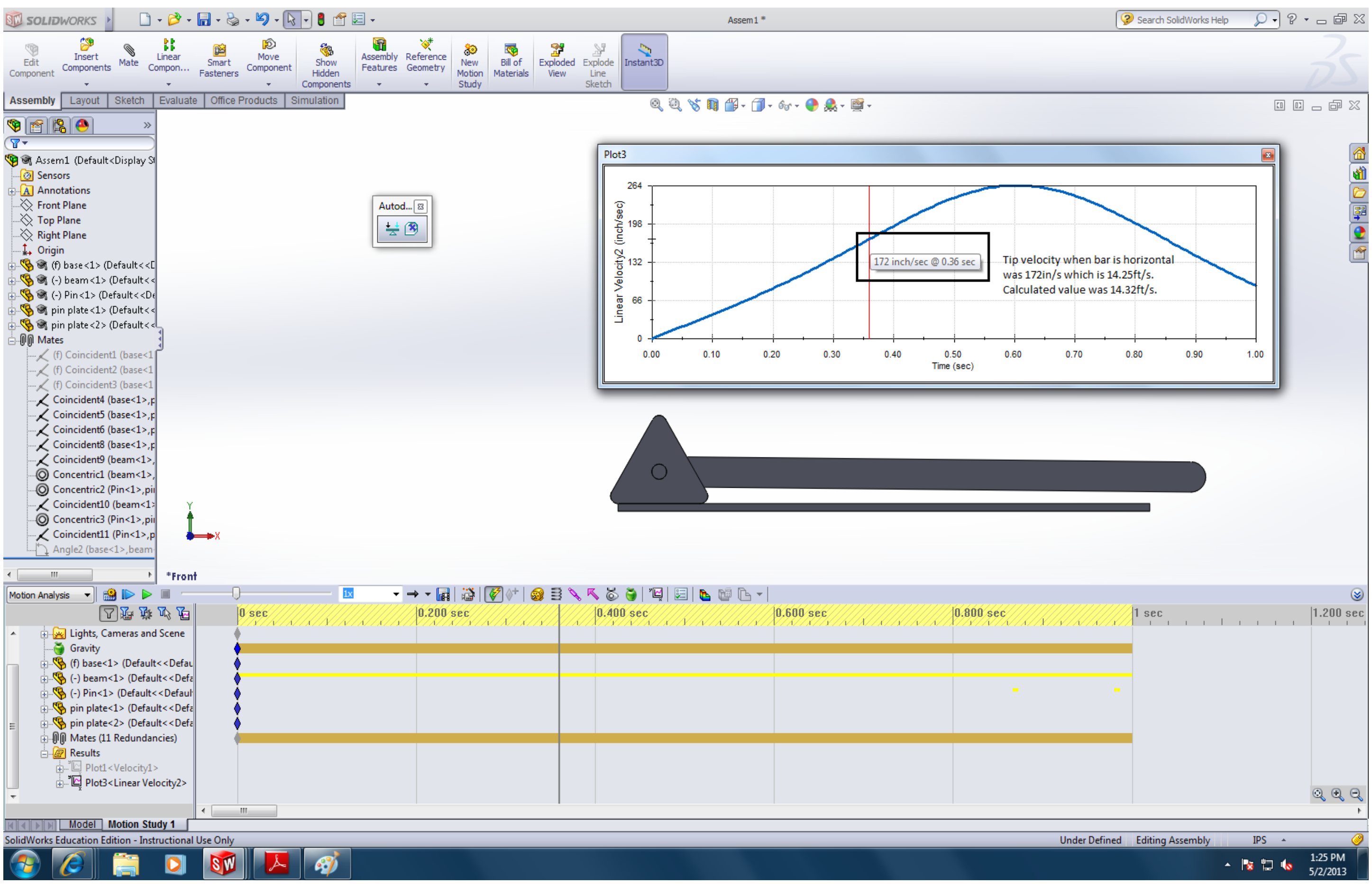

FIGURE 5 SOLIDWORKS MOTION STUDY SHOWING AGREEMENT WITH THEORETICAL SOLUTION.

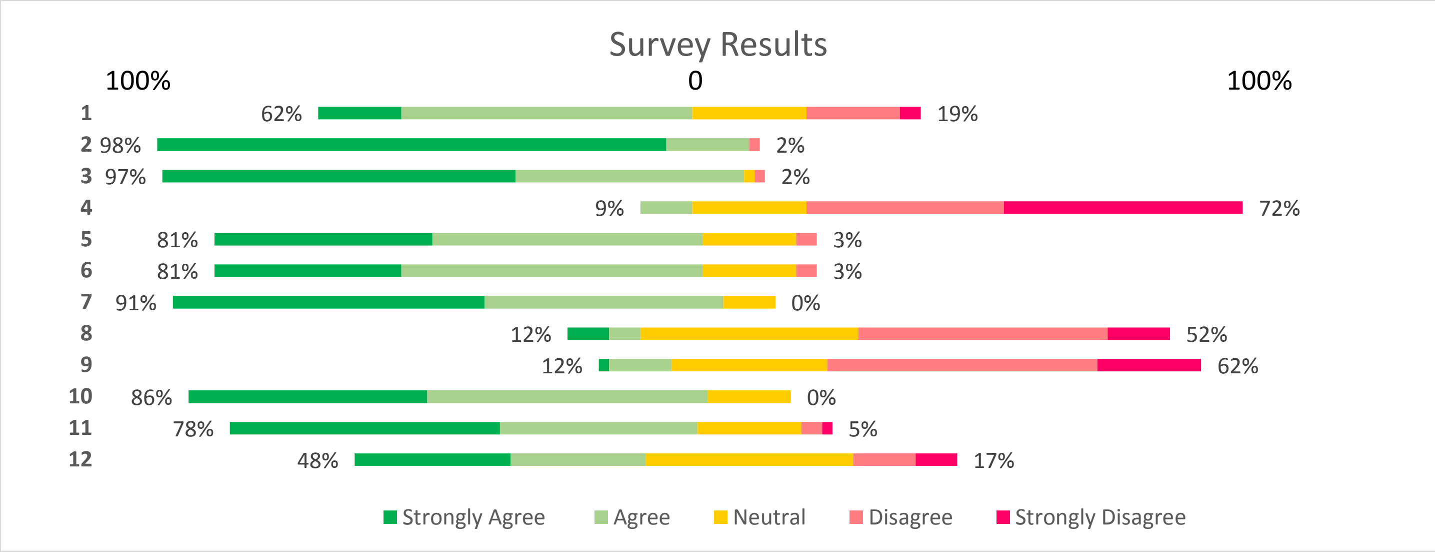

FIGURE 6 LIKERT SCALRE RESPONSES TO TWELVE SURVEY QUESTIONS

voluntarily completed the survey. The survey consisted of twelve Likert scale questions.

Adhering to the format suggested in [xii], Likert scale results are presented as a percentage of respondents centered at "neutral", with agreement with the prompt on the left in green and disagreement with the prompt on the right in red. The total percentage of responses to the left and to the right of "neutral", i.e. the sum of "strongly agree" and "agree" is shown as a label on each side. To limit "Acquiescence bias" one-fourth of prompts were keyed in the negative direction.

The survey only indirectly measures the effectiveness of the video library. As all students utilize the library, the ability to complete the simulations is an indirect measure of the tools assisting them. In retrospect, it may have been valuable to include a direct question about the video library. Students were also asked to report the number of hours they spent on SolidWorks each week, responses were: Mean: 3.70, Mode: 3, Max: 10, Min:1, Standard Deviation: 1.54, N: 58.

This section will consider the questions in order and discuss both the rationale for the question and my interpretation of the responses.

1. *My prior coursework prepared me to use SolidWorks in this course.* For the majority of respondents, prior coursework is a full semester of *Engineering Graphics and Design* three semesters prior and a single project in *Statics* one semester prior. Students indicated agreement by a margin of approximately 3:1, and this is interpreted as general satisfaction with the prerequisite structure but with significant room for improvement.
2. *My use of SolidWorks improved as a result of this course*. This question directly tests one of the conjectured benefits. Overwhelming agreement (98%) indicates to the author that the exercises provide an appropriate challenge to students to expand their proficiency in SolidWorks.
3. *SolidWorks is a good tool for performing numeric simulations.* This question tests the suitability of SolidWorks to this use. Overwhelming agreement (97%) suggests to the author that SolidWorks is an appropriate tool for generating numeric results that are comparable to theoretically derived results.
4. *SolidWorks should be removed from the course or made optional.* This question tests overall validity of this initiative. Students disagree with this statement by an 8:1 margin suggesting that a strong majority believe the course is better with SolidWorks than without.
5. *SolidWorks helped me envision the problems better.* A test of the "kinematic visualization" result, eighty-one percent agreement including thirty-six percent strong agreement suggests that SolidWorks is effective in helping students envision problems.
6. *The act of constructing the model helped me to better understand the mechanics of the problem.* I had imagined the act of construction to be a distinct experience from manipulating the constructed model, but identical results with question 5 suggests that perhaps there is no real distinction in the minds of the students.
7. *I feel confident I will be able to use SolidWorks in future courses because of the use in this class.* No disagreement suggests students have gained sufficient confidence in SolidWorks to use it in courses later in the program.
8. *The time invested in SolidWorks is not proportional to the benefit.* The question is poorly worded with an implied bias towards time spent in SolidWorks *in excess* of benefit. The mean time spent per week reported by the students was 3.7 with a mode of 3 hours per week. The response of only 10% in strong disagreement indicates relatively large ambiguity in the student population. Whereas the previous responses clearly indicate there are perceived benefits, the population is not so well convinced the benefits are worth the significant time investment.

9. *I didn't really trust SolidWorks, I could always fudge a number to get the answer the others got.* This exact sentiment was expressed by some students in prior years and was included here as a quantitative measure of its prevalence. A margin of 5:1 disagreement suggests that this phenomenon is less prevalent than I had feared.
10. *The ability to verify my own solutions was rewarding to me.* Included to test the conjecture that SolidWorks was better than "back of the book" answers. Very large agreement suggests this intended consequence is achieved.
11. *I liked building the SolidWorks models.* Test the conjecture that students enjoyed working in SolidWorks, 15:1 agreement suggests that this activity is less of a burden on students than I originally feared.
12. *At some point in the semester, I started to trust the SolidWorks result more than my hand calculations.* A frivolous prompt placed by the researcher in search of the holy grail of this endeavor. It is not clear what response would be selected by a student whose trusts his or her hand calculations *as much as* SolidWorks, or if this happened at no definable point in the semester, or if it had been the case prior to the semester. Mixed results may indicate a brand-new level of student confidence with SolidWorks but may also indicate that the researcher is an amateur at designing surveys.

CONCLUSIONS

Survey results indicating levels of satisfaction with the activity exceeded the author's expectations and indicate that the project is worth continuing. Despite a significant time investment reported by the participants (an average of 3.7 hours per week), a strong majority believe it should be retained as a requirement in the course (Q4). The ability to check one's own work (Q10) is both a new and important skill that can benefit students significantly when introduced in the sophomore year. All of the conjectural results described in the first section were confirmed by direct survey. The author concludes that the inclusion of SolidWorks not only improves the teaching of Dynamics, but strengthens the entire engineering program by equipping students with the tools for lifelong learning early in their career.

We plan on continuing this use of SolidWorks in the *Dynamics* course and may expand its application to other courses. The results of Question 1 show there is room for improvement in the preparedness of students for this experience. We particularly need to address the special needs of transfer students who may get transfer credit for a graphics course using another application, (e.g. AutoCAD), and therefore will have no preparation for SolidWorks before taking the *Dynamics* course. We will also refine the questionnaire for the spring of 2014 to test the perceived value of the tutorial videos.

REFERENCES

i W. Whiteman, K. Nygren, Achieving the Right Balance: Properly Integrating Mathematica Software Packages into Engineering Education. *Journal of Engineering Education*, July 2000.

ii B. Hodge, W. Steele, A Survey of Computational Paradigms in Undergraduate Mechanical Engineering Education. *Journal of Engineering Education*, October 2002.

iii A. Mazzei Integrating Simulation Software into an Undergraduate Dynamics Course: a Web-based Approach. *Proceedings of the 2003 American Society of Engineering Education Annual Conference and Exhibition.*

iv R. Flori, M. Koen, D. Oglesby, Basic Engineering Software for Teaching ("BEST") Dynamics. *Journal of Engineering Education*, January 1996.

v C. Demetry, J. Groccia, A Comparative Assessment of Student Experiences in Two Instructional Formats of an Introductory Materials Science Course. *Journal of Engineering Education*, July 1997.

vi Phillip J. Cornwell, Dynamics Evolution - Chance or Design. *Proceedings of the 2000 American Society of Engineering Education Annual Conference and Exhibition.*

vii D. M. Fraser, R. Pillay, L. Tjatindi, J. M. Cace, Enhancing the Learning of Fluid Mechanics Using Computer Simulations. *Journal of Engineering Education*, October 2007

viii R Stanley and G. DiGiuseppe, An Efficient Way to Increase the Engineering Student's Fundamental Understanding of Thermodynamics by Utilizing Interactive Web Based Animation Software. *Proceedings of the 2010 American Society of Engineering Education Annual Conference and Exhibition.*

ix M.R. Stein. A Classical Mechanics Course in an Electronic Classroom: Challenges and Rewards. *Proceedings of the 2009 American Society of Engineering Education Northeast Section Annual Meeting.* April 2009. University of Bridgeport, Bridgeport, CT.

x M.R. Stein. A Classical Mechanics Course in an Electronic Classroom: Challenges and Rewards. *Proceedings of the 2007 American Society of Engineering Education Northeast Section Annual Meeting.* April 2007. University of Rhode Island, South Kingston, RI

xi P. Boyle, Electronic Course Packaging for Statics and Dynamics: A review of Effort, Reward and Potential. *Proceedings of the 2007 American Society of Engineering Education Annual Conference and Exhibition.*

xii Naomi B. Robbins, Richard M. Heiberger, Plotting Likert and Other Rating Scales, 2011 Joint Statistical Meetings - American Statistical Association. Miami Florida, July 30th, 2011