

Incorporating IMU Technology to Demonstrate Concepts in Undergraduate Dynamics Courses

Ms. Rachel Vitali, University of Michigan

Rachel Vitali is a doctoral candidate in the Mechanical Engineering department at the University of Michigan, where she also received her B.S.E. in 2015 and M.S.E. in 2017. Her research interests include computational and analytical dynamics with applications to wearable sensing technology for analysis of human motion in addition to incorporating technology into undergraduate courses for engaged learning.

Dr. Noel C. Perkins, University of Michigan

Noel Perkins is the Donald T. Greenwood Collegiate Professor of Engineering and an Arthur F. Thurnau Professor in Mechanical Engineering at the University of Michigan. He earned his PhD at U. C. Berkeley in 1986 (Mechanical Engineering) prior to joining the faculty at Michigan. His research interests draw from the fields of computational and nonlinear dynamics with applications to the mechanics of single molecule DNA and DNA/protein complexes, wireless inertial sensors for analyzing human motion, and structural dynamics, topics on which he has published over 150 publications in archival journals and conference proceedings.

Dr. Cynthia J. Finelli, University of Michigan

Dr. Cynthia Finelli is Associate Professor of Electrical Engineering and Computer Science, Associate Professor of Education, and Director and Graduate Chair for Engineering Education Research Programs at University of Michigan (U-M). Dr. Finelli is a fellow in the American Society of Engineering Education, a Deputy Editor of the Journal for Engineering Education, an Associate Editor of the IEEE Transactions on Education, and past chair of the Educational Research and Methods Division of ASEE. She founded the Center for Research on Learning and Teaching in Engineering at U-M in 2003 and served as its Director for 12 years. Prior to joining U-M, Dr. Finelli was the Richard L. Terrell Professor of Excellence in Teaching, founding director of the Center for Excellence in Teaching and Learning, and associate professor of electrical engineering at Kettering University.

Dr. Finelli's current research interests include student resistance to active learning, faculty adoption of evidence-based teaching practices, the use of technology and innovative pedagogies on student learning and success, and the impact of a flexible classroom space on faculty teaching and student learning. She also led a project to develop a taxonomy for the field of engineering education research, and she was part of a team that studied ethical decision-making in engineering students.

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Introduction

Dynamics is historically challenging for students to understand and transfer concepts to new contexts in future classes. It is especially difficult for students seeing the material for the first time to imagine motion with static illustrations. As was noted in [1], "...dynamics is the study of motion, but textbooks and chalkboards, the traditional classroom teaching tools cannot show that motion." Furthermore, those traditional large lecture style teaching methods (i.e. note taking, book problem solving, etc.) typically only passively engage students with the material.

Active learning, on the other hand, has been shown to be an effective technique to positively affect the quality of education across a number of STEM fields [2, 3]. This study aims to introduce the use of inertial measurement units (IMUs) as an active learning intervention in an otherwise traditional (lecture based) engineering course in dynamics. IMUs are relatively inexpensive and versatile enough to employ in a large lecture setting without the need for a dedicated laboratory. The IMUs in this study incorporate three-axis MEMS accelerometers and angular rate gyros together with on-board memory. These sensors have the added benefits of being relatively small (1.5"x1"x0.5"), not requiring students to provide their own hardware (i.e. smartphones), and allowing for standardization for conducting experiments. The intervention documented in this paper represents the first of three levels that will systematically increase students' engagement with the technology. This Level 1 intervention consists of two experimental demonstrations designed to expose important and/or commonly misunderstood concepts identified in the literature [4, 5]. *We hypothesize the experiments will increase student conceptual understanding of the material covered in the course.*

Methods

This Level 1 intervention took place in an introductory dynamics course required for three different programs within the engineering college at a large, research-intensive university. The major topics covered in the course are three-dimensional particle motion, planar rigid body motion, and basic vibrations. It should be noted there is no lab associated with this course and that students previously practiced concepts solely through homework (problems selected from textbooks).

Participants

The undergraduate introductory dynamics course spans several engineering disciplines at a large public university. One semester (Fall '16) consisted of 3 sections, which enrolled a total of 172 students, 151 of which completed surveys at the beginning and end of the semester. This represents the control group who completed the course without the IMU intervention. The two subsequent semesters (Spring '17, Fall '17) consist of 7 sections, which enrolled a total of 451 students, 362 of which completed surveys at the beginning and end of the semester. This represents the intervention group who participated in (instructor-created, instructor-led) demonstrations. In a given semester, every section was taught by a different instructor, but there were repeat instructors between semesters.

Survey Instrument

At the beginning and end of the semester, students complete an online survey for extra credit that includes a validated instrument known as the Dynamics Concept Inventory (DCI) [4, 5]. The DCI measures conceptual understanding of introductory engineering dynamics via 29 questions focused on 14 important and/or commonly misunderstood concepts. For example, two concepts focus on the rolling without slipping condition and Coriolis acceleration. The results of this survey will evaluate our hypothesis that this intervention will increase student conceptual understanding of dynamics.

To compare students' change in conceptual understanding, we compute gains in DCI scores. This value represents how much the student's understanding increased normalized by how much understanding they could gain. Gains are defined in [3] as

$$\frac{\text{post score} - \text{pre score}}{100\% - \text{pre score}}$$

where the pre- and post-scores are the overall scores representing the proportion of questions the student answered correctly.

IMU Experiments

For this intervention, two experiments were demonstrated in class after which the students completed demonstration-related assignments. The first experiment (Fig. 1) focused on measuring and understanding the Coriolis acceleration in the context of a particle. The IMU was attached to a slider (the particle) free to slide along a rotating arm. An approximately constant force was applied to the string to generate a constant moment on a shaft that rotated the arm. The rotating shaft was rigidly attached to the arm, thus the constant moment created a constant angular acceleration of the arm. The experiment included the phase of motion where the slider stuck to the arm, followed by the phase when it slid outwards along the arm (ultimately impacting a stop). Students modeled this experiment by deriving the equations of motion of the slider (with the attached IMU) as a point mass and were asked a series of conceptual questions to be answered using the data harvested from the IMU's accelerometer and angular rate gyro.

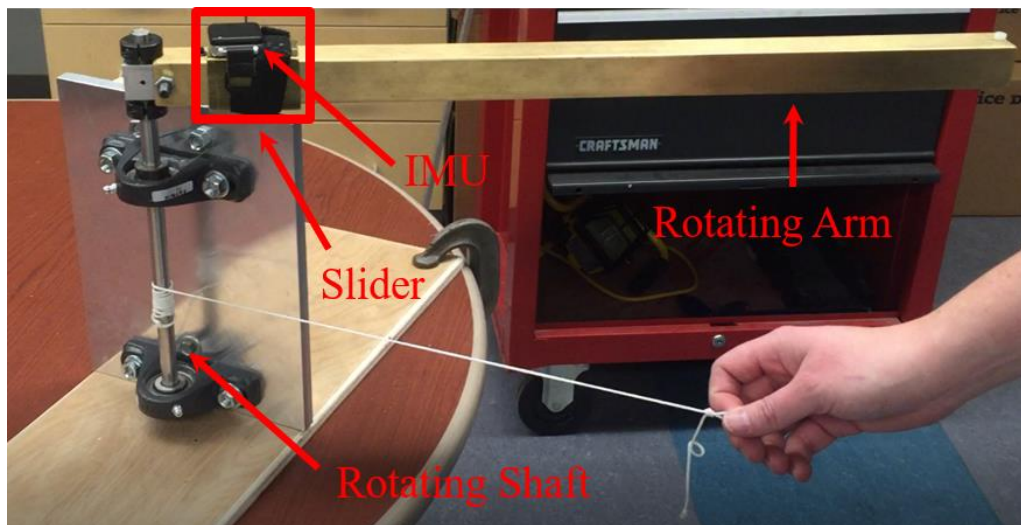


Figure 1: Experimental set-up of a rotating arm with a slider that demonstrates the Coriolis acceleration.

The second experiment was designed to study rigid body kinematics, rolling without slipping, and Newton's second law for a rigid body. Two versions of this experiment were offered in different semesters. The first version (Fig. 2a), demonstrated in Spring '17, consisted of 3 IMUs attached at three locations on a wheelchair; namely, the outer perimeter of a wheel, near the axel of the same wheel, and on the back of a chair. The second version (Fig. 2b) of the experiment, demonstrated in Fall '17, consisted of 2 IMUs attached at radially-symmetric locations on the underside of a Frisbee. In both versions, the object was pushed to produce initial linear and angular velocities that then allowed to roll freely thereafter subject to dissipative effects.

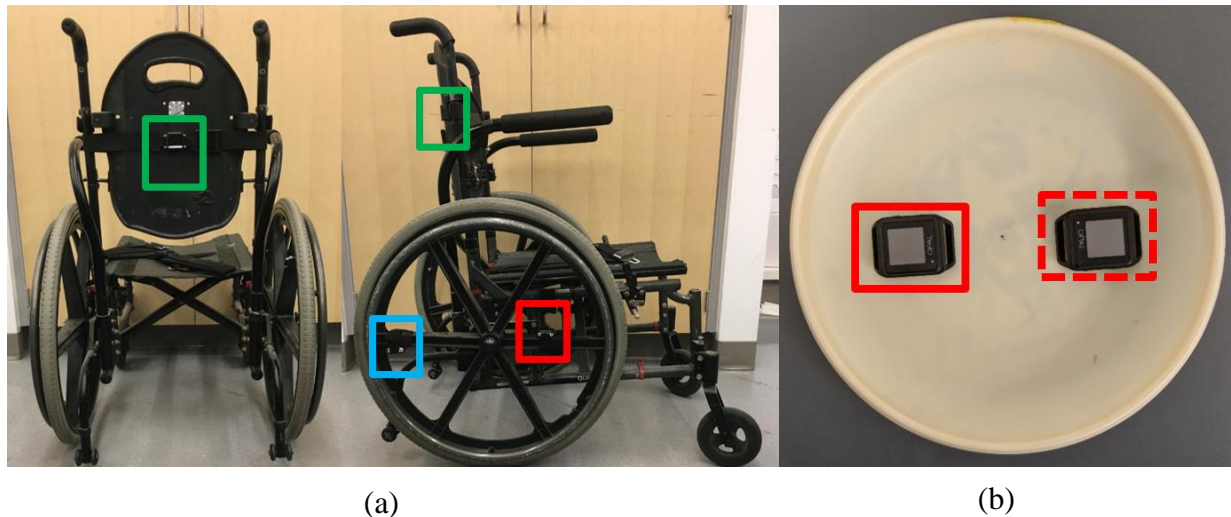


Figure 2: The two versions of experiment 2. (a) The wheelchair version included three IMUs located on the back of the chair (green), on a wheel near the outer perimeter (blue), and on the same wheel near the axel (red). (b) The Frisbee version included two IMUs located radially-symmetric on the underside. The IMU in the solid red box collected data for the assignment whereas the IMU in the dashed red box was added to minimize the effects of an eccentric mass.

Following the demonstrations in class, the students were given the relevant data collected with the IMUs to complete an assignment designed to reveal key concepts in kinematics and kinetics.

Follow-On Assignments

For the first experiment, students first estimated the angular acceleration of the rotating arm that they would use to develop a linear analytical expression for the angular velocity. Then, they drew free body diagrams of the slider when it was sliding along the length of the rotating arm. Using Newton's second law, they developed an equation of motion of the slider in the radial direction that they solved numerically for radial velocity and radial position. These results were then used to estimate the normal lateral force acting on the slider, which has components from the Coriolis acceleration and angular acceleration. They then compared the magnitudes of these components, which reveals the Coriolis component is significantly larger than the angular acceleration component.

For the second experiment, the first version (Fig. 2(a)) had a section focused on the kinematics of the wheel as a rigid body. Specifically, students looked at the angular velocities collected by the IMUs at the two positions on the wheel to determine they were the same. Then, they resolved the components of acceleration of one IMU in the body frame of the other to determine the

accelerations were different in magnitude and direction, but were very similar in their (out of phase) fluctuations. The kinetics portion required a free body diagram to determine the amount of force from the instructor's push at the beginning of the trial as well as the dissipative rolling resistance force after the push was over. For the second version (Fig. 2(b)), the students estimated the velocity of the center of mass of the Frisbee using only the angular velocity. Using this result, they computed the translational and rotational kinetic energies of the Frisbee. With the work-energy relationship, they determined the work done by the dissipative forces and then specified which forces acting on the Frisbee were doing work.

Results and Discussion

To discriminate between students who put forth genuine effort to complete the survey from those who may not have, we used three inclusion criteria: amount of time spent taking the survey, number of questions answered, and longest run of the same answer (e.g. selecting response "a" repeatedly). Out of a total of 442 students who completed both surveys, 21 students were excluded from our sample based on these criteria (giving a total of 145 students in the control group and 346 in the Level 1 intervention group).

Initial Assessment

The figures below describe the DCI item *difficulty* and item *discrimination* at the beginning and end of the semester for the control and intervention groups. Item *difficulty* (the horizontal axis in Fig. 3 on the next page) is the total percentage of students that answered the item correctly, so a higher score on this scale indicates an easier item [7]. An increase in item *difficulty* indicates that over the semester, the concept tested by that questions was, in general, better understood by the students. Less than 0.2 means the item is likely too difficult and greater than 0.8 means the item is likely too easy.

Item *discrimination* (the vertical axis in Fig. 3 below) is the correlation between students' right or wrong score on the item with their total score, so a higher score on this scale indicates the item was a good indicator of student overall knowledge [7]. An increase in item *discrimination* indicates the concept tested by the question was more effective in distinguishing between students' overall understanding of the DCI concepts. This means students that understood a specific concept better at the end of the course likely understood more of the DCI concepts overall. On the other hand, a decrease in item *discrimination* indicates the concept was less effective, and students might understand the concept in this specific context well, but not the DCI concepts as a whole. Below 0.2 means the item is testing a different construct compared to the rest of the survey.

In Fig. 3, the different colored vectors point from the scores at the beginning of the semester (circles) to the end (triangles) of the semester. The different colors correspond to different concepts and the numbers refer to the question (or item) number on the DCI. The rightward trend means more students answered the question correctly at the end of the semester. The upward trend means the students that understood the concept tested in these questions in general understood more of the material covered by the DCI. This figure is only intended to give a representative view of how student performance changed over the course of a semester without the intervention.

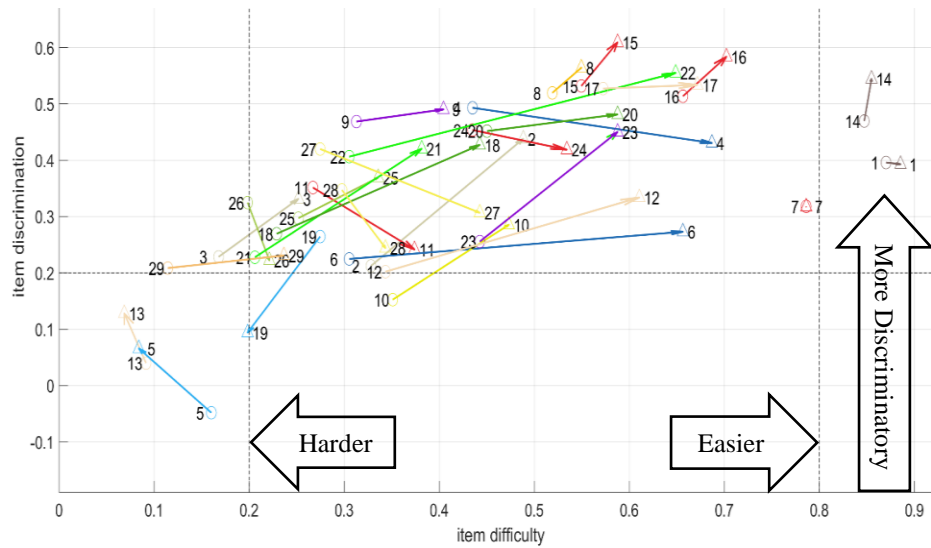


Figure 3: Item discrimination and item difficulty map by item for the control group. Numbers refer to the item number on the DCI, circles denote start of term, and triangles denote end of term. The vertical dashed lines represent the generally accepted range of item difficulties. The horizontal dashed line represents the lower limit for item discrimination.

In Fig. 4 below, the average change in item discrimination and item difficulty for a subset of concepts is shown. These concepts are the ones chosen as the foundation for the experiments that were demonstrated in class. The concept scores alone do not reliably determine student's understanding of specific concepts [7], but we use the average change in concept scores as an indicator of whether the experiments were having the desired effect on student conceptual understanding. The solid vectors denote the control group and the dashed vectors denote the intervention group. Given the small differences between the vectors, the intervention appears to have a limited effect on student understanding of the concepts we designed the experiments around.

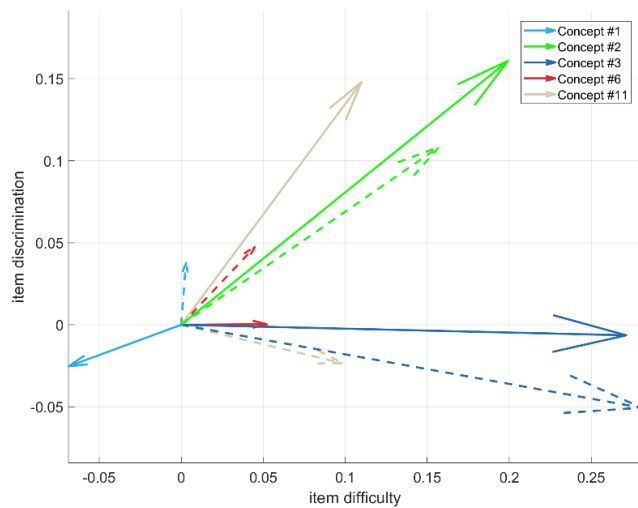


Figure 4: Item discrimination and item difficulty map by concept for the control (solid) and intervention (dashed) groups.

Quantitative Assessment

After confirming normality and homogeneity of variance assumptions, an Analysis Of Variance (ANOVA) was conducted on the DCI total scores to determine if any sections in the either the control or intervention groups tested significantly different from the other sections in their treatment group. The ANOVA for the beginning of semester survey ($F(2,142)=0.59$, $p=0.56$) confirms that for the control group, the students in each section start with the same level of knowledge. The ANOVA for the end of semester survey ($F(2,143)=0.98$, $p=0.38$) confirms students received the same level of instruction independent of instructor. Therefore, all control sections' data are aggregated into a single control group data set. This is also true for students in the Level 1 intervention group for the beginning ($F(6,339)=0.41$, $p=0.88$) and end ($F(6,339)=1.26$, $p=0.27$) of semester surveys. Similarly, all Level 1 intervention sections' data are aggregated into a single Level 1 intervention group data set.

The descriptive statistics for the groups are documented in Table 1 below. For the Welch's t-test performed on the DCI beginning of semester scores, the control group did not significantly differ from the Level 1 intervention group ($t(275.5) = -1.96$, $p = 0.06$). This implies that, at the start of the term, the students in the control semester did not significantly differ from the students in the Level 1 intervention. For the Welch's t-test performed on the DCI end of semester scores, the control group still did not significantly differ from the Level 1 intervention group ($t(255.1)=-0.05$, $p=0.65$), implying that the Level 1 intervention had limited impact on student conceptual learning.

Table 1: Mean (standard deviation) of scores on the 29-item DCI at the beginning of the semester (pre), end of the semester (post), and overall gain.

	pre %	post %	gain
Control	37.7 (14.6)	46.1 (18.3)	0.14 (0.22)
Level 1 Intervention	40.6 (14.9)	46.9 (17.2)	0.10 (0.23)

Although, the end of semester DCI percentage scores are not significantly different, the scores can be broken down by concept to determine if the Level 1 intervention group tested better or worse on a subset of questions representing a specific concept. The difference in performance between the students in the intervention group and those in the control group was statistically significant for Concept #3 ($t(256.5)=-1.98$, $p=0.04$), with the intervention group scoring higher. This concept concerns angular velocities and angular accelerations of a rigid body can vary with time, but not with location on the rigid body. This concept was used to design one of the iNewton experiments and represents a key concept stressed during the follow up assignments.

Conclusions and Future Work

Overall, the Level 1 intervention had a limited impact on improving student conceptual understanding of dynamics concepts. This intervention to the traditional teaching method still only requires the passive engagement of the students with the material (i.e. observing the demonstrations), which essentially maintains the same type of learning environment as the control group. The instructor describes the concepts exposed by the experiments while the students engage in effectively the same type of analysis as a homework problem and without performing the experiment. This is not altogether unsurprising given the results reported by Hake in [3]. Hake found that little to no active engagement of the students with course material in otherwise traditional courses yield significantly smaller gains [3].

The “level 1” intervention described in this paper did not exploit the active and hands-on learning that can arise from using this technology in an otherwise lecture-only course. Our larger research design is to next introduce level 2 and level 3 interventions that systematically grow the active and hands-on learning potential. The level 2 intervention consists of instructor-created, *student-led* experiments in which students are given IMUs to run pre-defined experiments outside of class. The final and level 3 intervention consists of *student-created, student-led* experiments where students propose an experiment of their own conception (with instructor feedback) to conduct with the IMUs outside of class. We expect to see increases in conceptual understanding as student engage more actively with the technology and therefore explore more fully the class concepts.

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