Work in Progress: Hands-on Engineering Mechanics with a Three-Dimensional Laboratory Unit

Dr. Md Rashedul Hasan Sarker, University Of Indianapolis

Md Rashedul H Sarker is an Assistant Professor at R.B. Annis School of Engineering at the University of Indianapolis (UIndy). Prior to joining at UIndy, he worked as a lecturer at The University of Texas at El Paso (UTEP). He also earned his Ph.D. at UTEP. His teaching and research interests include active learning, project-based learning, energy harvesting, and developing sensors using multi-functional materials

Dr. Najmus Saqib, University Of Indianapolis

Najmus Saqib is an Assistant Professor in the R.B. Annis School of Engineering at the University of Indianapolis (UIndy). Saqib received his Ph.D. in Mechanical Engineering from Colorado School of Mines (CSM), focusing on "Optical Diagnostics of Lithium-Sulfur and Lithium-Ion Battery Electrolytes using Attenuated Total Reflection Infrared Spectroscopy". He likes to use innovative pedagogical techniques to facilitate student learning.

Dr. George D. Ricco, University Of Indianapolis

George D. Ricco is an assistant professor of engineering and first-year engineering coordinator at the University of Indianapolis. He focuses his work between teaching the first two years of introductory engineering and engineering design and research in student progression. Previously, he was a special title series assistant professor in electrical engineering at the University of Kentucky, and the KEEN Program Coordinator at Gonzaga University in the School of Engineering and Applied Science. He completed his doctorate in engineering education from Purdue University's School of Engineering Education. Previously, he received an M.S. in earth and planetary sciences studying geospatial imaging, and an M.S. in physics studying high-pressure, high-temperature FT-IR spectroscopy in heavy water, both from the University of California, Santa Cruz. He holds a B.S.E. in engineering physics with a concentration in electrical engineering from Case Western Reserve University. His academic interests include longitudinal analysis, visualization, semantics, team formation, gender issues, existential phenomenology, and lagomorph physiology.

Megan Hammond, University of Indianapolis

Assistant Professor in the R.B. Annis School of Engineering at the University of Indianapolis.

Mr. Jared Hilt

Mr. James T Emery II, University of Indianapolis

**Hands-on Engineering Mechanics with a Three-Dimensional
Laboratory Unit (Work in Progress)**

Abstract

A novel working station for demonstrating the fundamentals of engineering mechanics in both three- and two-dimensional spaces has been developed. The equipment allows undergraduate students to perform hands-on activities to aid their understanding of topics such as force components in multiple dimensions, vector dot products, vector cross products, and mixed triple products which are often difficult to visualize in three-dimensions. While several educational laboratory modules for mechanics courses currently available on the market can demonstrate basic two-dimensional systems, equipment that can accurately realize three-dimensional systems are rare. Also, these systems are often improvised and lack the necessary accuracy for multiple lab demonstrations. The experimental setup described herein consists of a highly customizable base unit and a variety of add-on tools, such as pulleys, force sensors, and hanging weights. These allow for accurate demonstration of the foundational principles of mechanics in three-dimensional spaces. The Engineering Mechanics Laboratory Unit has been built by a combined effort of faculty, staff, and students at the R.B. Annis School of Engineering at the University of Indianapolis (UIndy). The unit is currently being used by students enrolled in Statics (MENG 210) in the Mechanical Engineering Program at UIndy. Ongoing efforts include designing lab modules for use in additional courses, such as Dynamics (PHYS 360) and Mechanics of Solids (MENG 300). The efficacy of the laboratory unit is currently being assessed in the classroom using a mixed methodological approach. First, students' perceptions of the apparatus and core concepts are analyzed using a reflective journaling protocol that is evaluated by a team of experts in mechanical engineering. Second, students provide detailed field ethnographic notes while engaging with the apparatus and the lab work itself. Third, student work from this semester is being compared to previous years' evaluations that were undertaken without the implementation of this novel approach.

Introduction

Statics is one of the very fundamental engineering mechanics courses taken by students for many engineering programs [1-5]. At its core, statics is a theoretical course that is attempting to mimic ideal real-world scenarios. At the heart of this work, lies the desire to make these ideal scenarios into physical or kinesthetic demonstrations.

Theories that expound upon and methodological frameworks for analyzing kinesthetic activities and experimental lab work have existed in the domain of engineering education for quite some time [6, 7], and certainly are well documented within the mechanical engineering discipline [8-13], ranging from the study of manufacturing, any number of forays and iterations of the teaching of statics, interdisciplinary work heavily involving mechanical engineering design and mechanical engineering students, senior capstone projects, and a barrage of industry-collegiate partnership research projects. One common theme among these works is that students are more engaged with where their interests lie, and if the community of mechanical engineering

just did more real engineering, that somehow student engagement would skyrocket! Of course, this pervasive attitude among some researchers begs the question of who gets to define real engineering, and the bigger issue of what happens when student interests are wrong to pursue [14] ? Our approach has been to focus on incremental laboratory experiments to increase their effectiveness at engaging students in regularly-taught courses over multiple-semesters.

One of the impetuses behind our research is the pervasive undercurrent within the past decades that mechanical engineering has issues of student persistence, engagement, and retention, and somehow this can be affected by fixing or reformatting introductory courses [3, 15]. While overall graduation rates among mechanical engineers have been studied to the point where they are practically campfire stories, navigating the space for improvement within individual courses can seem treacherous, or at times pointless. Certainly, student engineering performance within introductory coursework is shown to be at times haphazard, with radical differences in grade variance across similar sections of the same courses irrespective of overall course size [16, 17] being a key factor that may outweigh any instructor-led initiatives across small and large introductory course sections [2, 10]. While these studies have not extended their longitudinal analysis to statics and dynamics courses, they do make a reasonable case that variance among courses and professors is anyone's game to address and subsequently attenuate.

A strong mathematical background is imperative to be successful in engineering mechanics. In statics, students learn about multiple concepts fundamental to mechanical engineering, including planar forces, breaking a force into its components in Cartesian vectors in two- and three-dimensional spaces, the equilibrium of particles and rigid bodies in two- and three-dimensional spaces, the moment of a force about a point and about an axis, force-couple systems, and reducing a system of forces into a force couple system. These concepts are fundamental to solving other engineering problems, including analysis of structures, frames, machines, etc. Instructors typically cover these concepts by explaining them at first on the board, on presentation slides, or by distributing handouts to the students [4]. It is commonly observed (and assumed) that students tend to solve statics problems in two-dimensional space more comfortably compared to solving them in three-dimensional spaces. Students seem to easily apply trigonometric relations to breakdown planar forces into their components in two-dimensional spaces, while in three-dimensional spaces they usually perform a breakdown of forces into a vector expression. At this point, students struggle to visualize the scenario of the concepts in a three-dimensional Cartesian coordinates and different planes. Many attempts have been undertaken to improve students' concepts of statics in three-dimensional spaces, including online problem solving [4, 18, 19] with real time feedback and modeling kits to demonstrate textbook problems [10, 20-22]. Although online practice can give real-time feedback, it cannot replace a hands-on, kinesthetic activity. On the other hand, while model kits improvised by an instructor can provide hands-on learning, these often can demonstrate only a very few statics concepts in three-dimensional spaces and are not customizable to demonstrate any other concepts. There are many experimental setups readily available in the market, as shown in Figure

1, to perform experiments within statics and they predominantly cover experiments in two-dimensional spaces.

Figure 1: (a) Statics System from Pasco www.pasco.com, (b) Forces and Moments kits from TecQuipment www.tecquipment.com, and (c) Statics Forces module from Armfield www.discoverarmfield.com.

In this paper, the authors present a highly customizable laboratory unit to demonstrate numerous engineering mechanics concepts in both two and three-dimensional space. The structure was designed by a group of faculty, students, and staff. Add-on tools can be purchased locally or custom-made based on the course requirements. Initially the laboratory unit was made with wooden frames and plywood and later with an aluminum extrusion frame and plates. The setup is envisioned for both lecture classrooms and lab classrooms. The figure below shows the setup with aluminum extrusion frames and aluminum grid panels. This setup is heavier and best suited for a lab classroom on lab-benches.

Figure 2: Experimental setup made with aluminum extrusion frames and plates.

A lighter version is also under development for a lecture classroom which can be assembled and disassembled within a couple of minutes by an instructor or a group of students.

The lighter version of the setup will be made with 1-inch outer-diameter plastic-coated steel framing rails ($\frac{1}{2}$ lb per foot), clamp-on framing fittings, panel hanger fittings, and $\frac{1}{2}$ -inch thick acrylic sheets (3 lb per square foot). The light framing rail and acrylic sheets with clamp-on framing fittings will make the setup easy to carry and can be assembled and disassembled within a very short period by an instructor or a group of students in the classroom. The lighter version of the setup is expected to weigh less than 8 lb.

The wooden frame was used in a fall 2019 statics course. The authors presented the following three experimental demonstrations using the designed laboratory unit:

1. Demonstration of a vector dot product.
2. Equilibrium of particles in three-dimensional space.
3. Demonstration of vector cross product.

Experimental Demonstrations

Demonstration of a Vector Dot Product

The vector dot product is used in statics to find out the angle between two lines in a three-dimensional space. Students can easily find the angle in two-dimensional spaces using trigonometric relations. However, when it comes to finding the angle between two lines in three-dimensional spaces, students tend to have difficulty visualizing the concept of a vector dot product and struggle to express the vector form of the line.

To help students' understanding the following demonstration was developed as a hands-on activity. One sample configuration of cable attachments into our mechanics laboratory unit is shown in Figure 3. Different groups of students have different orientations of the cable attachments. Students choose the origin of the Cartesian coordinate system by themselves and measure the position of points A, B, and C using a measuring tape or a ruler. After measuring the coordinates of the points, students find the vector expressions and magnitudes of cables AB and BC. To measure the angle between the cables AB and BC, they then apply a vector dot product as shown in Equation 1.

Figure 3: Two different views of a vector dot product demonstration.

$$\overline{AB} \cdot \overline{BC} = AB \cdot BC \cos\theta \quad (1)$$

A prototype of the laboratory unit was made using a wooden frame and quarter-inch thick plywood to engage students. Figure 4 shows the equipment and students engaging during the laboratory experiment to apply a vector dot product. A protractor is also provided to the students to enable them to verify their results. Students hold the protractor along the plane of the two cables to measure the angle and compare it with their calculated results.

Figure 4: (a) A prototype of the laboratory unit for engineering mechanics. (b) Student engagement.

Equilibrium of Particles in Three-dimensional Spaces

Students also learn to solve statics problems by applying the equilibrium of forces in two- and three-dimensional spaces. Again, they comfortably execute trigonometric relations to find the force components in two-dimensional spaces and apply the equilibrium conditions. However, students struggle when it comes to the same situation in three-dimensional spaces where they have to express the forces into vectors and use the concept of a unit vector. There are many experimental setups that can be found on the market where students can perform some hands-on activities on force equilibriums in two-dimensional spaces but none of these are useful in three-dimensional spaces.

To demonstrate a force equilibrium in three-dimensional spaces, a sample problem was selected where students had to find the weight of a crate suspended by an array of cables. This problem was reconstructed using the mechanics laboratory unit. Figures 5 and 6 show the sample problem schematic, and the reconstruction of the problem using the laboratory unit with a free-body diagram, respectively.

Figure 5: A sample problem to demonstrate force equilibrium in three-dimensions.

Figure 6: (a) and (c) Recreating the problem from Figure 5 using the experimental setup. (b) The corresponding free-body diagram.

In Figure 6 (c), the weight of the crate, W_0 , was balanced by three other weights, W_1 , W_2 , and W_3 , with an array of cords and pulleys. Low-friction pulleys (Ultra Pulley from Vernier www.vernier.com) were selected for the setup. When, W_0 is pushed downwards and then released, the weight W_0 comes back to its initial position due to very low-friction of the pulleys.

The students' task is to find out the value of weight W_0 . As low-friction pulleys were used, the tension in the three cables holding W_0 will have the same value as W_1 , W_2 , and W_3 , respectively. Of the four hanging weights, the values of W_0 , W_1 , and W_2 are covered with tape

and the weight of W_3 is revealed to the students, so that they can identify the tension in one of the cables.

In the exercise problem shown in Figure 5, the coordinates of points B, C, and D are given but in the reconstructed demonstration students can choose any point along the cable. Measuring tape and slide calipers are provided to the students for taking measurements. In Figure 6 (c), students consider point A as their Cartesian coordinate origin. For cables AB, AC, and AD students select the points B, C, and D on the same plane as the top surface of the grid panel (three arrows pointed to the points B, C, and D). To locate point A, instead of an eyeball measurement, students place a ruler on top of the grid panel and use another ruler or measuring tape from point A to the ruler on the grid panel. After this, students mark on the ruler. This way students can find the vertical distance from the top surface of the grid panel to point A. Students use a ruler or measuring tape again similarly to find the distances from the mark on the top of the ruler laid down on the grid panel to the points of B, C, and D.

After measuring the tension in the cable AC and expressing the tensions in cables AB, AC, and AB in vector form, students apply the appropriate equilibrium conditions to find the value of W_0 . The lowest percentage difference was reported as 1.98%.

$$\sum F = 0 ; \bar{T}_{AB} + \bar{T}_{AC} + \bar{T}_{AC} + \bar{W}_0 = 0 \quad (2)$$

where

$$\bar{T}_{AB} = T_{AB} \hat{\lambda}_{AB}$$

$$\bar{T}_{AB} = T_{AB} \hat{\lambda}_{AB}$$

$$\bar{T}_{AB} = T_{AB} \hat{\lambda}_{AB}$$

$$\bar{W}_0 = W_0 \hat{\lambda}_{W_0}$$

Demonstration of Vector Cross Product

In statics, students are introduced to force-couples and force-couple systems, where they learn about the moment of a couple, equivalent couples, reducing a system of forces to a force-couple system, which requires the application of vector cross product. As students tend to learn better with hands-on activities [23], a demonstration was prepared using the mechanics laboratory unit as shown in Figures 7 and 8.

A clear plexiglass sheet was placed on top of the three force sensors. The readings on the force sensors due to the weight of the plexiglass were zeroed and three different loads (F_1 , F_2 , and F_3) were placed exactly on top of the sensors over the plexiglass sheet and then the corresponding reaction forces were measured using the sensors. The reaction forces from the

sensors should be the same as the weights of F_1 , F_2 , and F_3 . Three dual-range force sensors along with a LabQuest Mini data acquisition interface (from Vernier: www.vernier.com) were used for this demonstration.

In this demonstration, students reduce the parallel force system into a force-couple system ($R = \sum F$; M_O^R) and find the position vector, r , of the resultant force, R , by applying the relation shown in Equation 3. The origin point, O , can be any point selected by the students on the plexiglass plane.

$$M_O^R = r \times R = \sum M_O^F \quad (3)$$

After determining the position, r , of the resultant force, R , students place a load equivalent to resultant force ($R = \sum F$) on that position and measure the resulting reaction forces on the force sensors. At this point, the corresponding reaction forces on the sensors should again be the same as the weights of F_1 , F_2 , and F_3 . The lowest percentage difference was reported as 2.5%. In this demonstration students use markers on top of the plexiglass where the force sensor probes were placed. The accuracy of the results depends on how well the students can place the stack of weights on the midpoint of the marker. In the future, small eyehooks and dents will be made on top of the plexiglass to aid students to stack the weights accurately. This demonstration provides a hands-on activity for the application of a vector cross product and the reduction of parallel forces into a force-couple system.

Figure 7: Schematic demonstration of an equivalent force-couple system.

Figure 8: Demonstration of an equivalent force couple system.

A subtle difference that we would like to address through an extension of this work lies in the notion that different majors within introductory mechanical engineering courses may or may not benefit from reinforcing the curriculum with hands-on learn best practices [10]. Coller's work demonstrates that while electrical engineering students greatly benefited from such a redesign of an introductory statics course, that counterintuitively, mechanical engineering students did not. The net contention of such a study is that perhaps mechanical engineering students have some natural propensity towards statics principles or a proclivity with laboratory hands-on experiments that outranks their peers' abilities, or that electrical engineering students are so inexperienced with mechanical systems that increasing hands-on activities boosts their comprehension.

Conclusions and Future Work

The mechanics laboratory unit described here was first used in the fall of 2019 offering of statics, with a prototype made out of a wooden frame and plywood. Ongoing efforts are aimed at producing multiple laboratory units built with cold-drawn aluminum frames. Add-on tools like pulleys, weights, cords, force sensors, rectangular metal beams, custom-made clamps for the unit, and deflection gauges can be used with this unit to demonstrate force equilibrium in two-dimensional spaces, the principle of moments, beam reactions, and beam deflections. Five finished aluminum units will be used in the Fall 2020 offering of Statics to identify the efficacy of the laboratory unit with the following mixed methodological approach: first, students will complete reflection and design notebooks throughout the semester that are going to be analyzed by a team of experts; second, students will have ethnographic field notes from their experiences with the apparatus itself, and third, an analysis of the previous years' coursework outcomes without the implemented apparatus will be undertaken in the final work.

The design journals/notebooks completed by the students will be based on self-journaling or auto-ethnographic journal methodologies [24, 25]. In our methodology, the students will complete a meta-ethnography of sorts, and will be educated in multiple types of design journaling methodologies, and choose the frameworks and tools that they believe work best for reporting their observations. The evaluators will identify if there is any evidence of stages of design as the students learn and record their notes [26, 27]. The evaluators will also identify if there is any pattern of iteration, simulation, or any other type of common design activity when interacting with the apparatus. After that, the evaluators will start addressing the question, “Do the students who exhibit high proclivity with the apparatus seem more like experts navigating the tools or more like apprentices?” This will require the evaluators to give seasoned mechanical engineers a chance to explore the apparatus and record their observations while addressing a novel problem. Finally, the course outcomes from previous years without the implemented apparatus will be analyzed.

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