Work in Progress: A Novel 2D Vectors Hands-on Lab Exercise for a First Year Engineering Mathematics Laboratory

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Abstract - **Studies show that teaching mathematics using an application-oriented, hands-on approach helps students grasp and understand the topics much better as compared to a lecture-based mathematics course. Starting Fall 2016, New Jersey Institute of Technology (NJIT) offers such a course loosely based on the Wright State University model to engineering students placed in pre-calculus courses. Throughout the course, students are introduced to engineering problems and applications that rely on concepts of mathematics. This course has lecture, recitation and laboratory components. The lecture provides an overview of relevant topics in engineering analytical methods that are most heavily used in the core sophomore-level engineering courses. These topics are reinforced through solving problems in a lab environment. This paper will discuss a new hands-on lab project that is being introduced in Spring 2018 to help students understand the concept of two-dimensional vectors. A model of a human arm has been designed to demonstrate the application of two-dimensional vectors and calculation of reaction forces. The same model can also be used to demonstrate the application of the law of cosines to measure the bicep muscle length and applications of direct and inverse kinematics for a two-link robot. Use of a simplistic model that must be manually loaded and measured provides a visual demonstration of the concepts and applications of mathematics as discussed in the lecture as well as presented in the textbook. The model has the additional advantage of being inexpensive as it is 3D printed in-house. We plan to assess the effectiveness of this activity using student surveys. We also look forward to gathering feedback from other conference attendees about this hands-on lab exercise and hope to refine it further for future semesters.**

Index Terms – Application-oriented, Engineering mathematics, First year introductory course, Hands-on lab.

INTRODUCTION

Incoming first year students at our mid-size STEM institution should ideally start in calculus I in the mathematics sequence before they can advance to sophomore-level core engineering courses. However, a high percentage of these students are placed into remedial pre-calculus courses, and do not reach calculus I until their second semester, or even their second year. Students placed into pre-calculus courses lose their drive to do well in these courses as they find it difficult to establish a connection between mathematics and engineering. Therefore, they struggle to keep up with the coursework. In addition to a loss in motivation, any delay in entry to calculus I or failure in calculus I is almost automatically equivalent to at least one additional semester of stay at college. In an attempt to solve this problem, our institution decided to offer an "Engineering 101" (ENGR101) introductory course loosely based on the Wright State University (WSU) engineering mathematics education model, starting in Fall 2016.

WSU has developed a model with National Science Foundation (NSF) funding to increase student retention and motivation. This model is currently being tested at or has fully been adopted in 40+ engineering schools nationwide [1-3]. The idea is to teach mathematics to incoming first-year students using an application-oriented, hands-on introductory course. This course provides an overview of relevant topics in engineering analytical methods from core sophomore-level engineering courses. These topics are reinforced through extensive examples of their use in lab exercises.

The course, ENGR 101, is a 4-credit course meeting for 90 minutes of lecture two times a week, and 90 minutes of recitation and 90 minutes of lab meetings once a week. It is a required course for all engineering students placed into pre-calculus courses. The course has been significantly revised from the original WSU model to cater specifically to students, who are taking pre-calculus and are one to two terms behind the expected starting point [4, 5]. For the first two offerings of ENGR101 at NJIT, the lab projects done were virtual simulations (on computer). Starting Fall 2017, we started moving gradually towards more hands-on physical labs.

The following sections discuss in detail a new hands-on lab developed to help students understand the concepts of two-dimensional vectors and trigonometry using a human arm model.

HANDS-ON LAB

Success in nearly all areas of engineering requires the ability to resolve vector quantities, such as force, position, velocity, acceleration, displacement (position), electric and magnetic fields, and momentum, into vector components. Students placed in pre-calculus courses very often struggle to visualize and resolve vector quantities into their component form. Moreover, the concept of a reaction force and its components only adds to the confusion. Introducing and reinforcing these concepts early in an introductory engineering math course in conjunction with a simple hands-on lab offers an opportunity to reinforce these fundamental engineering concepts.

The musculoskeletal system presents a number of examples for which force vectors can be effectively studied. Examples, as seen in Figure 1, include the mechanics of the arm, hip, knee, and ankle. The human arm is also an example of a two-link robot. Many robots are programmed to mimic human motion and are used to perform simple repetitive tasks such as lifting and moving objects. The positions and angles of joints and end-points are found using direct and inverse kinematics, which often requires the application of the law of sine and cosine.

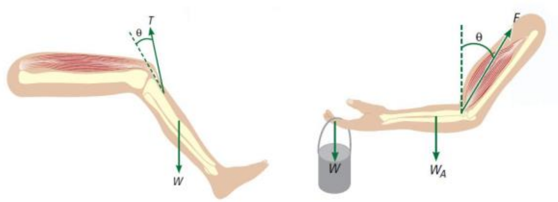


FIGURE 1
EXAMPLES OF MUSCULOSKELETAL FORCE VECTORS

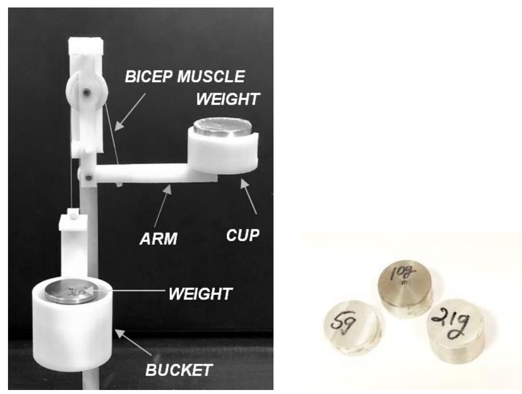
Two-link arm apparatus

A human arm and bicep muscle model is used to demonstrate the application of vectors in engineering and applications of the law of sine and cosine to find muscle length, muscle attachment angle, and end position distance. PASCO Scientific offers a human arm model, as shown in Figure 2, which simulates the bicep and triceps muscles using strings. By pulling on a force sensor that is attached to a string the tension in the string can be measured. The string tension creates a moment about the elbow joint which lifts a weight placed in the hand.


FIGURE 2
PASCO SCIENTIFIC HUMAN ARM MODEL

Here we present a two-link robot - arm-muscle model that can be cheaply fabricated and assembled from 3D printed parts.

The model consists of an arm with a cup on one end which holds the load that needs to be lifted (Figure 3). A string, representing the muscle, connects the lower arm, passes over a pulley and attaches to a bucket. The arm movement is controlled by placing a load into the bucket. The string passes over the pulley to minimize friction and is connected to the lower arm by a pin. Adding weights in the bucket creates the bicep muscle force that enables the arm to lift the load in the hand. As opposed to using a force sensor, by physically adding the weights into the bucket students can directly measure the force. The use of weights to manually load and collect data can give insight that is often lost with more automated models used for data acquisition. By comparing the number of weights (see Figure 3b) in the bucket to the weights in the cup a more tangible understanding of the force and lever system can be made. Resolving the muscle force into its *x-y* components it is easy to see the origin of the reaction forces. A tab fabricated on the stand prevents the arm from moving to the left as a result of the *x*-component of the muscle force. The tab applies the reaction force to keep the arm stationary when loaded.



(a) (b)

FIGURE 3
(A) TWO-LINK ARM APPARATUS (B) WEIGHTS

The goal for the students is to balance the weights in the bucket and in the cup to achieve a state of equilibrium with the arm in the horizontal position, as shown in the Figure 3. Increasing weights are placed in the cup. Students record the weight required in the bucket to balance the weight in the cup. A sample table for entering data is shown in Table I.

TABLE I
SAMPLE TABLE FOR STUDENTS

Weight in the cup (g)	2	5	10	20	25
Weight in the Bucket (g)					

Calculation of Reaction Forces

The lengths of the muscle attachments from the elbow joint are measured to find the muscle attachment angle. Using the free body diagram shown in Figure 4, the reaction forces, R_x and R_y, are calculated.

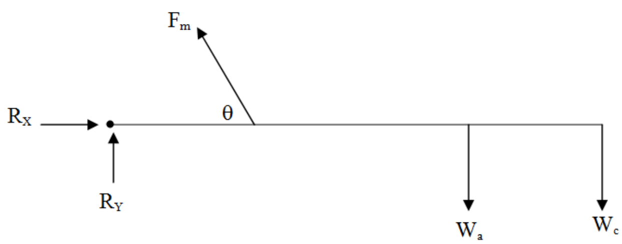


FIGURE 4
MUSCLE-ARM FREE-BODY DIAGRAM

R_x, R_y – Reaction forces on the joint
F_m – Force applied on the muscle
W_a – Weight of the arm.
W_c – Weight on the cup

Application of Law of Cosines

As an additional exercise, students are asked to balance the weights such that the arm is positioned at 45° below the horizontal (Figure 5). In this position the muscle length $\overline{OB}$ is calculated using the law of cosines.

$$\overline{OB}^2 = \overline{OA}^2 + \overline{AB}^2 - 2\overline{OA}\,\overline{AB}\cos 135^0$$

The vector $\vec{r}$ from the shoulder to the hand is also calculated using the law of cosines and then expressed in component form.

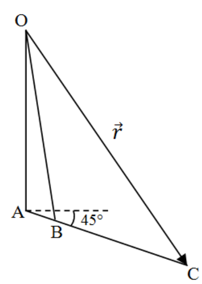


FIGURE 5
TWO-LINK ROBOT WITH 135^0 ANGLE BETWEEN THE LINKS

The forward kinematics equation to find the components of $\vec{r}$ is given by:

$$r_x = \overline{AC}\cos 45^0$$
$$r_y = \overline{OA} + \overline{AC}\sin 45^0$$

STUDENT FEEDBACK

Student feedback on physical, instead of virtual simulation (on-computer), labs were collected through a survey at the end of the semester. The question specifically asked was – "Please comment on the physical l abs that you did. Did those help you understand the topic better than the virtual labs?" Listed below are some of the comments received categorized as positive, neutral and negative. In general, the students liked having a hands-on experience and could understand the concept better. A couple of students found the virtual labs to be more intuitive. A few students do feel that some of these topics can be major-specific and they won't benefit from learning them.

Positive Responses:
• I believe doing the lab in person instead of virtually helped me understand the concept more. This is the case because I am a visual learner.
• Yes, working hands on for me is a better experience. It is clearer because I am actually tweaking with the real-life problem.
• Yes (3)
• The physical labs helped me to understand the topic better compared to the virtual labs because I could actually see and build upon what's going on.
• Yes, the physical lab is a great way to see what is actually going on in the virtual labs. It gives students a hands-on view about how the problems work rather than just putting in a number on the virtual lab.
• Physical labs were definitely better than the virtual labs. It helped me understand topics overall much better. (3)
• Physical Labs gave a better representation of the lab as compared to virtual labs.
• I think that the both were beneficial. But, the Physical Lab is a better implementation for learning for the career.

Neutral Responses:
• The physical labs helped me understand the course material just as well as the virtual labs.
• It helped a little bit but not that much.
• I knew most of the physical lab material from my FED 101 class, so I didn't really learn much more but nevertheless, the physical lab was a nice change.

Negative Responses:
• The virtual labs were definitely much easier to understand than the physical labs.
• They helped only a few certain majors.
• The virtual labs were better to me in my opinion. This is because our class had multiple snow days, so we only did 1 physical lab which wasn't the same.
• They were fun, but they didn't apply to my major and they weren't well explained enough.
• I was able to understand both labs equally, physically or virtually. I found the virtual lab were a bit more intuitive and easier to complete.

SUMMARY

A hands-on lab has been presented that uses an inexpensive 3D printed arm-muscle model to demonstrate applications of vectors and trigonometry for use in introductory engineering mathematics courses. Upon completing the lab, students should be able to:

1. Understand 2D vectors and apply them to engineering problems.
2. Understand and apply the law of cosines.
3. Be able to perform the direct kinematics for two-link robot.

The use of 3D printing in this experiment can also be used to inspire students to create their own examples of force vector systems. Overall, students liked the experience of reviewing the topic of vectors and trigonometry with a hands-on lab experiment and we plan to refine it further and run this again in Fall 2018 semester for a much bigger student population.

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