AC 2007-1174: A VERSATILE AND ECONOMICAL APPARATUS FOR EXPERIMENTS IN STATICS

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A Versatile and Economical Apparatus for Experiments in Statics

Abstract

A student's understanding of engineering concepts can be furthered through the use of hands-on experiments and demonstrations. For many students, the concepts of vectors, particle equilibrium, and rigid body equilibrium can be difficult to comprehend. In order to improve comprehension in these areas, we developed a single apparatus that provides for the operation of at least five experiments relevant to the study of statics. These experiments are well-suited for either laboratory studies or, due to the device's portability, for in-class demonstrations.

In this paper we present the complete design, including the bill of materials, assembly drawings, and assembly instructions for the apparatus. The apparatus is easily assembled from readily available parts and materials, especially sturdy, easily expandable, and very affordable (approximate cost of materials is $500).

In addition, we present the details of five experiments that can be performed utilizing the device. For each experiment, we provide the objective, procedure, and recommended data analysis. The five experiments are: 1) Particle Equilibrium: Tension Components in Cables of Independent Lengths; 2) Particle Equilibrium: Tension Components in Cables of Equal Lengths; 3) Particle Equilibrium: Equilibrium Position of a Pulley System; 4) Rigid Body Equilibrium: Tension in a Cable; and 5) Friction: Friction Force as a Function of Contact Angle. Each experiment can be compared to a theoretical analysis with good agreement, providing the student with a hands-on experience to advance the student's understanding of these concepts.

Introduction

Engineering is a hands-on practical profession and since the earliest days, laboratories have been an essential component of engineering education. However, over the span of modern engineering education, there has been a varied level of the importance placed upon laboratories.(1) Most recently, the recommendations of "Educating the Engineer of 2020" (2) as well as the new ABET criteria(3) have placed a renewed emphasis on laboratories and hands-on approaches. Many programs(4) now offer first-year engineering courses that attempt to make explicit connections between engineering, math and science. In many cases, these first-year courses offer a hands-on experience in the form of a project(5),(6),(7). While projects offer additional valuable experiences such as problems solving, teamwork, communications, and ethics, there is still a need for traditional laboratory experiences. Traditional laboratory experiences fulfill three roles as identified by Edward Ernst(8). First, the student learns how to be an experimenter. Second, the student learns new and developing subject matter. Finally, the student gains insight and understanding of the real world.

Perhaps the first universal opportunity for a student to experience an engineering laboratory in modern engineering curricula is in statics. This course is generally one of the first engineering topics covered outside of graphics and other first-year engineering experiences in many curriculums. However, a survey of 30 engineering programs indicates that there is rarely a lab associated with statics. This perhaps is not too surprising, as the number of credible labs associated with this course probably could not take up an entire semester of labs. In addition, some commercially available statics demonstration/lab equipment can be very expensive (in excess of $5000 for a single experiment). Nonetheless, there are valuable laboratory experiences within statics. In particular, for some students, statics can become a purely mathematical exercise(9),(10) and a laboratory experience and/or classroom demonstration can allow these students to better understand the physical concepts. It should be noted that classroom demonstrations are most effective when coupled with the requirement of having the students predict the answer in advance of observing the demonstration(11).

Our apparatus for experiments in statics is dubbed the "VectorSmith." In addition to the three roles of laboratory experiences described above, we believe that these laboratory experiences should provide students an alternative look at a particular problem. With this in mind, the five experiments we developed are classic problems presented in virtually all statics textbooks. This allows students with different learning styles a better opportunity to grasp the concept that the problem is conveying.

Yoder et al.(12) proposed the following guidelines for hands-on laboratory experiences for teaching engineering fundamentals:

1) the scale of the experiment should be in the normal range of the student's experience;
2) students should feel the physical process they are trying to measure;
3) differences between situations should be very noticeable and easily measured;
4) data collection tools should be crude and easy to use; and
5) data uncertainty and its implications are emphasized throughout.

The VectorSmith was designed with these guidelines in mind. Buckets filled with lead shot are used to provide forces in the range of 2 - 20 lbs, easy to read dual-unit spring scales are used to measure tensile forces, yard (or meter) sticks are used to measure lengths, and substantial changes to the geometry of the system are made to obtain noticeable changes in the forces. While not all of the experiments presented herein require the students to "feel" the process, they could be modified to do so. In complying with the above guidelines, one may make the assumption that the experiments must not be very accurate or provide only subjective data. This is not the case. These experiments show very good agreement with theory and are very repeatable. This is an essential requirement for mimicking the classic statics problems.

We currently use the VectorSmith in an introductory first-year experience and in an integrated Statics/Mechanics of Materials course. Both of these are traditional lab environments, where the students work in small groups to run the experiment and record data, then individually analyze data, discuss the results, and draw conclusions. The VectorSmith's low cost (about $500 for materials) and portability make these experiments appropriate to run as classroom demonstrations or in a recitation setting. With the recent wide use of laptop computers, the data can be gathered in 5-10 minutes then analyzed during the remaining class period or perhaps the following class period.

This paper describes the basic VectorSmith frame, a summary of the five experiments, an example and discussion of selected results, and appendices that include a bill of materials and a summary of the student worksheet for one experiment. Detailed assembly drawings as well as the laboratory worksheets for all five experiments can be obtained by contacting the first author via e-mail at williamsric@ecu.edu.

Description of the Apparatus

Figure 1: VectorSmith Frame

The experiment apparatus consists of a frame to which additional hardware can be mounted to allow for the running of a variety of experiments. The frame is constructed of extruded aluminum T-Slot framing members from 80/20 Inc.(13) This framing system can be ordered cut-to-length and is fastened together with screws, thus providing a custom low-cost, easy-to-assemble, light-weight frame. The frame, illustrated in Fig. 1, is 48" wide and 52" tall and weighs 25 lbs. Appendix 1 lists the bill of materials for the frame.

The VectorSmith is configured for the five experiments that are outlined in this paper by adding components to the T-Slots in the frame. The T-slots allow for positioning of the components anywhere along the top member of the frame or on either leg, thus allowing for variability among student lab groups. In addition, the frame is very versatile and easily adaptable to additional experimental hardware, including hardware facilitating 3-D experiments. Appendix 1 also lists the bill of materials required for each of the five experiments outlined in this paper.

Summary of Experiments

Experiment 1: Particle Equilibrium: Tension Components of Cables of Independent Lengths

This experiment is the classic problem of a weight hanging by two cables. In this experiment the student is given an unknown weight which is positioned along seven pre-determined locations of the cable (we actually use chain). Figure 2 illustrates the set-up at one of the locations. At each location the student records the tension in each cable by reading the value from each spring scale and records the geometry of the set-up by measuring the lengths of the sides of the triangle formed by the cables and the top of the frame.

The learning objectives of the experiment are:

1) utilize the Law of Cosines to solve for the angles of a triangle,
2) resolve a vector into its components,
3) apply the conditions of static equilibrium to graphically determine an unknown force, and
4) consider the sources of experimental uncertainty.

In the data reduction step, the student uses the Law of Cosines to calculate the necessary angles required to resolve the cable tensions into x and y vector components. In the data analysis step, the student creates two graphs. The first graph is a plot of the y-component of the tensions (of each cable and the sum of the two cables) vs. horizontal position. The second graph is a similar plot of the x-components of tension. Comparing these graphs to the analytical solution reinforces the concepts that the sum of the y-components of the tension are equal to the weight and the x-components are equal in magnitude while opposite in direction. Utilizing the graphs and the analytical solution, the students should conclude the magnitude of the weight, compare the empirically derived magnitude of the weight to the actual value, and discuss the sources of experimental uncertainty.

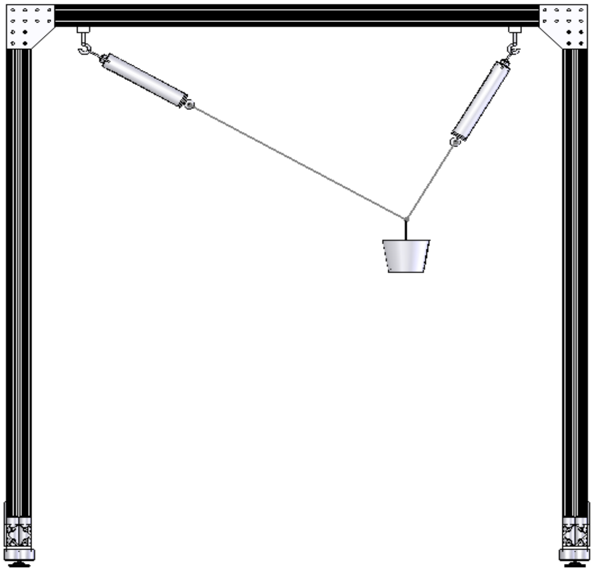

Figure 2: Example of Experiment 1 Setup

Experiment 2: Particle Equilibrium: Tension Components of Cables of Equal Lengths

This experiment is the classic problem of a weight hanging by two cables of equal lengths. In this experiment the student is given a known weight which is positioned in the center of the cable. The cable lengths are sequentially reduced to provide four different lengths. At each cable length the student records the tension in each cable by reading the value from each spring scale and records the geometry of the set-up by measuring the lengths of the sides of the triangle formed by the cables and the top of the frame.

The learning objectives of the experiment are:

1) utilize trigonometric functions to solve for the angles of a triangle,
2) reinforce the concept of geometric symmetry,
3) apply the conditions of static equilibrium to graphically determine the maximum tension , and
4) consider the sources of experimental uncertainty.

During the data collection, the student should observe that the tensions in each cable are approximately equal in magnitude. In the data reduction step, the student uses the trigonometric functions to calculate the angle of the cable relative to horizontal. In the data analysis step, the student creates one graph. The graph is a plot of tension vs. angle. The student is also required to determine and plot the theoretical solution. Comparing the experimental data to the theoretical solution reinforces the concept that the tension can far exceed the magnitude of the weight and, in fact, approaches infinity as the horizontal angle approaches zero. Utilizing the graph, the students should conclude that the tension approaches infinity as the angle approaches zero and discuss the sources of experimental uncertainty.

Experiment 3: Particle Equilibrium: Equilibrium Position of a Pulley System

This experiment is the problem of a set of two weights balanced on a pulley system as illustrated in Fig. 3. In this experiment the student is given a known weight which is free to move on a pulley cable system. A second known weight balances the system such that the first weight establishes its equilibrium position. The second weight is sequentially increased to provide five different equilibrium positions. For each value of the second weight, the student records the tension in each cable by reading the value from each spring scale and records the geometry of the set-up by measuring the length of the sides of the triangle formed by the cables and the top of the frame.

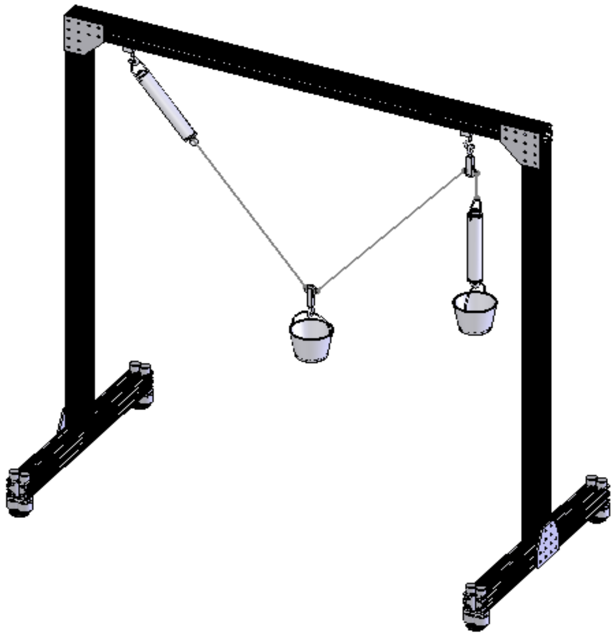

Figure 3: Example of Experiment 3 Setup

The learning objectives of the experiment are:

1) reinforce the concept of ideal pulleys,
2) develop an understanding of the concept of mechanical advantage, and
3) consider the sources of experimental uncertainty.

During the data collection, the student should note that the tensions in each section of the cable are approximately equal in magnitude. In the data reduction step, the student should determine the height of the suspended weight and the mechanical advantage of the pulley system. In the data analysis step, the student creates two graphs. The first graph is a plot of height vs. tension. The student is also required to calculate and plot the theoretical solution on this graph. Upon comparison of the experimental data to the theoretical solution, the student should note a disagreement between the data and the theoretical solution, thus reinforcing the concept of an ideal pulley (this also provides a good segue into the friction experiment presented below). The second graph is a plot of mechanical advantage vs. height. From this graph, the student should conclude that the mechanical advantage is a function of the geometry and diminishes as the suspended weight is raised. The students are also asked to comment on sources of experimental uncertainty.

Experiment 4: Rigid Body Equilibrium: Tension in a Cable

This experiment is the classic problem of a weight hanging from hinged beam supported by a cable as illustrated by Fig. 4. In this experiment the student is given a known weight which is positioned at varied locations along the length of the beam. At each position the student records the position of the weight, the tension in the cable by reading the value from the spring scale, and the geometry of the set-up by measuring the lengths of the sides of the triangle formed by the cable, the beam, and the side of the frame. The experiment is repeated with the beam at three different angles relative to horizontal.

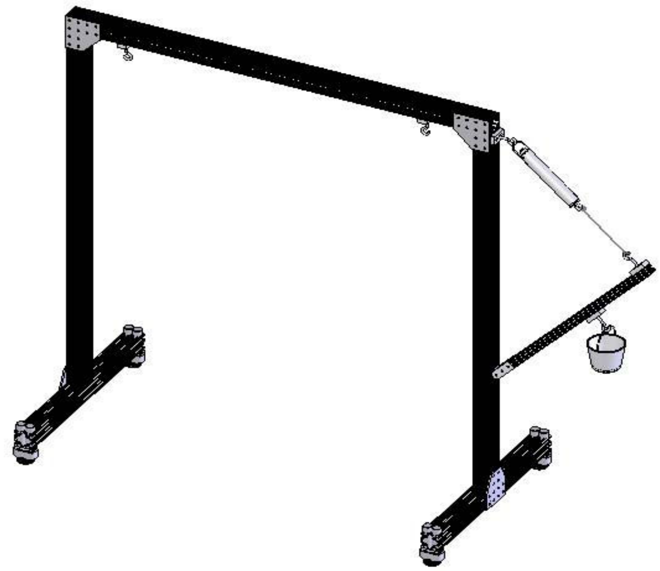

Figure 4: Example of Experiment 4 Setup

The learning objectives of the experiment are:

1) utilize the Law of Cosines to determine angles of a triangle,
2) apply the conditions of static rigid body equilibrium to determine the tension as a function of the position of the weight ,
3) expose the students to parametric analysis, and
4) consider the sources of experimental uncertainty.

During the data collection, the student should note that the tension in the cable increases as the weight is moved out along the beam. In the data reduction step, the student uses trigonometric functions to calculate the required angles of the cable and beam relative to horizontal. In the data analysis step, the student creates one graph. The graph is a plot of tension vs. position of the weight with each beam angle plotted as a separate series. The student is also required to determine and plot the theoretical solution. The students are asked to analyze the limiting cases of the beam position (beam angle ± 90° from horizontal) and discuss the sources of experimental uncertainty.

Experiment 5: Friction: Friction Force as a Function of Contact Angle

This experiment is the study of friction between a string and a stationary cylinder. In this experiment the student is given a known weight which is suspended by a heavy string connected to a spring scale. The string is wrapped around a fixed cylinder with varying contact angle. Figure 5 illustrates the setup for a contact angle of $\pi/4$. At each contact angle the student pulls on the spring scale and observes the maximum force achieved prior to the string slipping. The total force includes the weight and friction force and is recorded at each of six contact angles.

The learning objectives of the experiment are:

1) expose the student to an exponential relationship,
2) curve fit exponential data,
3) utilize a semi-log graph, and
4) consider the sources of experimental uncertainty.

In this lab, the student is provided the exponential relationship between the tension in the string on each side of the cylinder. In the data analysis step, the student creates two versions of the same graph. The graphs are a plot of tension vs. angle displayed on a linear scale and a semi-log scale. The student is required to plot the data and utilize the curve fitting capability of MS Excel® to determine the static coefficient of friction and then discuss the sources of experimental uncertainty.

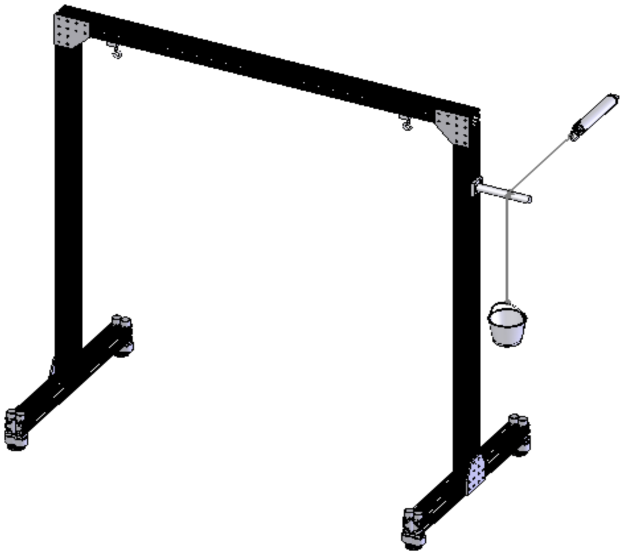

Figure 5: Example of Experiment 5 Setup

Results and Discussion of Selected Experiments

The apparatus described herein provides a set of experiments for courses in statics or, in some cases, freshman engineering experiences. These experiments can be run by the students as lab based experiments or by the instructor as demonstrations. An example of the student worksheet utilized for the particle equilibrium experiment (experiment 1) is included in Appendix 2. Figure 6 illustrates typical student collected and reduced data from experiment 1. From the graphical presentation, it is clear to the students that the y-components of the two tension vectors add to nearly the same value for all positions. While there is some error between the magnitude of the sum of the y-components of tension and the weight, we believe that this provides the student with a good basis for discussing sources of experimental uncertainty. We do not require a formal analysis of experimental uncertainty since this is covered later in our curriculum, however, we do strongly believe that it is important for students to begin developing an understanding of experimental uncertainty and ask them to comment on uncertainty in every lab write-up. The sources of uncertainty in this lab include the accuracy of the spring scales, the accuracy of the linear measurements, and the fact that we are ignoring the mass of the spring scales and chain.

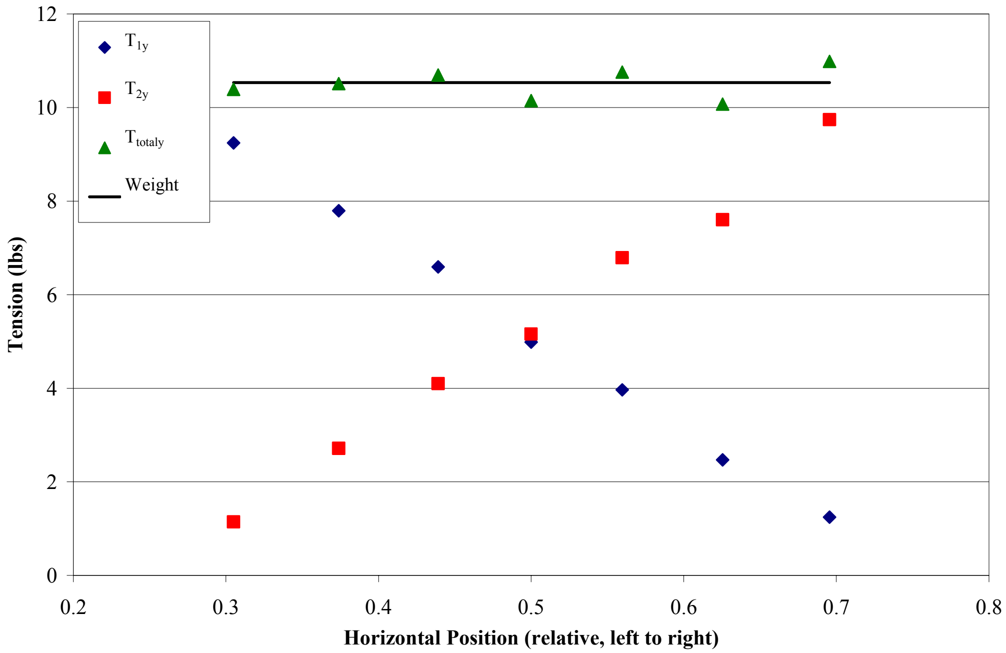

Figure 6: Typical Data, Experiment 1

One interesting source of uncertainty is that caused by the deflection of the spring scales themselves. In some of the experiments, such as experiment 1, all the geometric measurements are taken at the deflected state, so this source is nonexistent. However, we believe that using the non-deflected geometry or fixed deflected geometry provides a learning opportunity for the students. We use a fixed deflected geometry (with the weight hanging near the mid-point of the beam) in experiment 4. This introduces a small but measurable error in the analysis and is a point for discussion. This concept is useful for recall in the strength of materials course where the geometry of the deflected state is commonly ignored.

Figure 7 shows typical data from experiment 5 and, as illustrated, the experiment generates a very good exponential function. In this lab the student is also asked to graph the data on a semi-log scale, resulting in a line. The slope of the line is the coefficient of static friction. We found that the friction coefficients found by different groups of students were surprisingly consistent, with almost all groups' values in the range of 0.23 to 0.25.

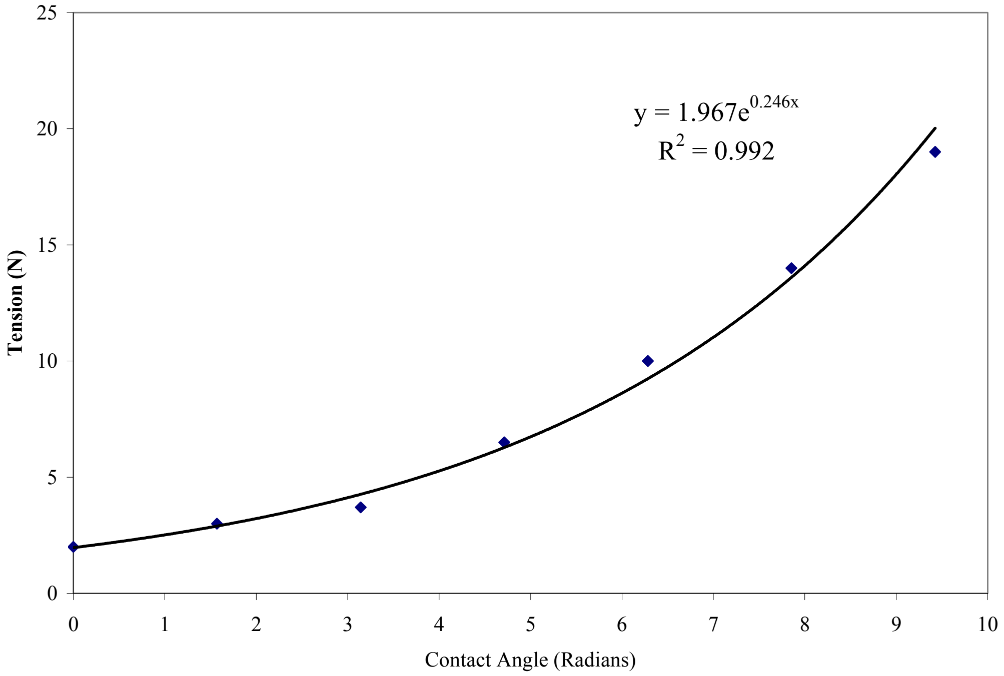

Figure 7: Typical Data, Experiment 5

Assessment

The VectorSmith has been utilized to run experiments in two courses within our program; a freshman experience course and a combined Statics and Strength of Materials course. In the freshman experience course, the students use the VectorSmith to conduct experiments 1 and 2. In the combined Statics and Strengths of Materials course, the students used the VectorSmith to conduct experiments 4 and 5. Experiment 3 will be introduced into the combined course. The available assessment data are indirect based on student surveys.

In the freshman experience course, the open-ended questions “What was the most valuable lab experience and why?” and “What was the least valuable lab experience and why?” were asked of the students. The lab experiences included solid modeling, a robot project lab, an energy conversion lab, an electric motors lab, an electric circuits lab, and the two VectorSmith labs. Eighty-six percent of the students (n=44) responded to the most valuable question, while 68% responded to the least valuable questions. Of those that responded, 40% rated the VectorSmith labs as the most valuable, giving reasons such as: “it related to class,” “it was applied,” “it helped my understanding,” “it was hands-on,” and “it was interesting.” Conversely, of those that responded, 16% rated the VectorSmith labs as the least valuable, giving such reasons as: “engineers are not concerned with tension,” “I learned it in high school physics,” and “I did not understand vectors.”

In the combined Statics and Strength of Materials course, the students (n=40) were asked to rate eleven labs in four categories using the following scale: 1: Strongly Disagree, 2: Disagree, 3:

Neutral, 4: Agree, and 5: Strongly Agree. The four categories were Timing (Timed well with the lecture material), Reinforcement (Helped me better understand the lecture material), Clarity: (The lab was easy to perform, understand and write up), and Overall Rating (1 = poor, 2 = fair, 3 = good, 4 = very good, and 5 = excellent). Table 1 summarizes the data across four lab sections for the Rigid Body Equilibrium and Friction Labs.

Table 1: Summary Results from Student Survey

Lab	**Timing**		**Reinforcement**		**Clarity**		**Overall Rating**	
	Mean	*Stdev*	*Mean*	*Stdev*	*Mean*	*Stdev*	*Mean*	*Stdev*
Rigid Body Equil.	4.05	0.52	3.97	0.76	3.73	0.65	3.93	0.72
Friction	3.92	0.98	4.14	0.71	4.08	0.80	4.25	0.73

Although both labs were rated in the “very good” range across all four categories there are several areas that warrant comments. In the rigid body lab, the students were asked “As the angle θ approaches 90° and -90°, what value does tension T approach? Show and explain each case using a FBD.” We found that many students were confused on what we were asking and had trouble correctly analyzing these limiting cases and we believe that this was the main contributor to the lower ratings in Clarity and Overall. It is our intent to either clarify this discussion question or replace it with a different discussion question. The relatively low rating of the Timing of the friction lab was attributed to fact that one instructor did not keep pace with the lecture schedule resulting in this lab running far out of sequence with the lecture material for that section. In fact, the lab sections where the lecture and lab were in sequence gave the friction lab a Timing rating of 4.22 whereas the out of sequence rating was a 3.43. It should be noted that the timing issue was recognized prior to the running of the lab and some lecture material was added to the lab by the lab instructor in order to bring the affected students up to speed.

Conclusions

The experimental apparatus (VectorSmith) described herein provides five meaningful and cost effective experiments in statics. The VectorSmith is expandable, portable, and can be used for classroom demonstrations or in a lab environment. The experiments provide good data that can be easily compared to analytical solutions, thus expanding the student’s understanding of a topic. Assessment data indicate that the labs are valuable to the students’ learning and understanding of the principles of vectors, static equilibrium, and friction.

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13. 80/50 Inc., 1701 S. 400 East, Columbia City, IN 46725, www.8020.net.

Appendix 1: Bill of Materials

Component Description	**Part Number**	**Quantity**	**Vendor**
Frame			
10 series extruded profile, cut to 44.75 inches	2020	2	80/20 Inc.
10 series extruded profile, cut to 24.00 inches	2020	2	80/20 Inc.
10 series extruded profile, cut to 48.00 inches	2020	1	80/20 Inc.
10 S 12 Hole 90° Joining Plate	4128	2	80/20 Inc.
10 S 12 Hole Tee Joining Plate	4125	2	80/20 Inc.
1/4-20 Furniture Style Glide	2203	4	80/20 Inc.
10 S 1"x2" Base Plate W/ 1/4-20 Tap in Center	2128	4	80/20 Inc.
2020 End Cap Yellow W/ Push-ins	2028YEL	6	80/20 Inc.
1/4-20 x 1/2" FBHSCS & Econ T-nut	3321	48	80/20 Inc.
1/4-20 x 1/2" SHCS	3062	8	80/20 Inc.
10 S Econ T-nut W/ 1/4-20 Thread	3382	8	80/20 Inc.
Additional Material: Experiments 1, 2, and 3			
10 S 1"x2" Base Plate W/ 1/4-20 Tap in Center	2128	2	80/20 Inc.
1/4-20 x 1/2" SHCS	3062	4	80/20 Inc.
10 S Econ T-nut W/ 1/4-20 Thread	3382	4	80/20 Inc.
Spring Scale	1757T39	2	McMaster Carr
Lead Shot (25 lbs)	9030K1	1	McMaster Carr
2.5 Qt Pail	4288T1	2	McMaster Carr
Chain, 5/64" diameter (per ft)	8951T17	10	McMaster Carr
Open Eyebolt (2", 1/4"-20, 20 per pack)	9490T4	1	McMaster Carr
S-hook, 9/64" (25 per pack)	9381T25	1	McMaster Carr
Threaded Connector	8947T14	2	McMaster Carr
Swivel Eye Sheave, (3/16" Rope)	3213T57	2	McMaster Carr
Rope, Braided Polyester, 3/16" (per 100 ft)	3852T36	1	McMaster Carr
Additional Material: Experiment 4			
10 series exturded profile, cut to 24.00 inches	1010	1	80/20 Inc.
1/4-20 x 7/8" SHCS & Econ T-nut	3305	1	80/20 Inc.
10 S Econ T-nut W/ 1/4-20 Thread	3382	3	80/20 Inc.
1/4-20 x 1/2" BHSCS & Econ T-nut	3393	4	80/20 Inc.
2020 End Cap Yellow W/ Push-ins	2028YEL	1	80/20 Inc.
10 S 0° 3" Arm Pivot	4197	1	80/20 Inc.
Chain, 5/64" diameter (per ft)	8951T17	3	McMaster Carr
Spring Scale	*1757T39*	*1*	*Materials Common to Above Experiements*
Lead Shot (25 lbs)	*9030K1*	*1*	
2.5 Qt Pail	*4288T1*	*1*	
Open Eyebolt (2", 1/4"-20, 20 per pack)	*9490T4*	*1*	
S-hook, 9/64" (25 per pack)	*9381T25*	*1*	
Threaded Connector	*8947T14*	*2*	
Additional Material: Experiment 5			
2"x2" End Mount Pressure Manifold Plate-Blank	2349	1	80/20 Inc.
1/4-20 x 1/2" SHCS	3062	4	80/20 Inc.
10 S Econ T-nut W/ 1/4-20 Thread	3382	4	80/20 Inc.
Twine, Nylon, 0.058" braided (per 240 ft)	2057T75	1	McMaster Carr
Delrin Rod	8497K31	1	McMaster Carr
Threaded Stud, 1/4-20 x 1"	98758A305	1	McMaster Carr
Spring Scale	*1757T39*	*2*	*Materials Common to Above Experiements*
Lead Shot (25 lbs)	*9030K1*	*1*	
2.5 Qt Pail	*4288T1*	*1*	
S-hook, 9/64" (25 per pack)	*9381T25*	*1*	

Appendix 2: Example Experiment Handout
Tension Components of Cables of Independent Lengths

Background

The vector stand utilizes linear scales to measure the tension force in a rope or cable. A weight can be supported by two cables while measuring the tension and geometry (lengths or angles). The basic arrangement of components is illustrated in Fig. 1. The length of the left cable system is defined as L_1. The length of the right cable is defined as L_2. The height of the cable system is defined as H.

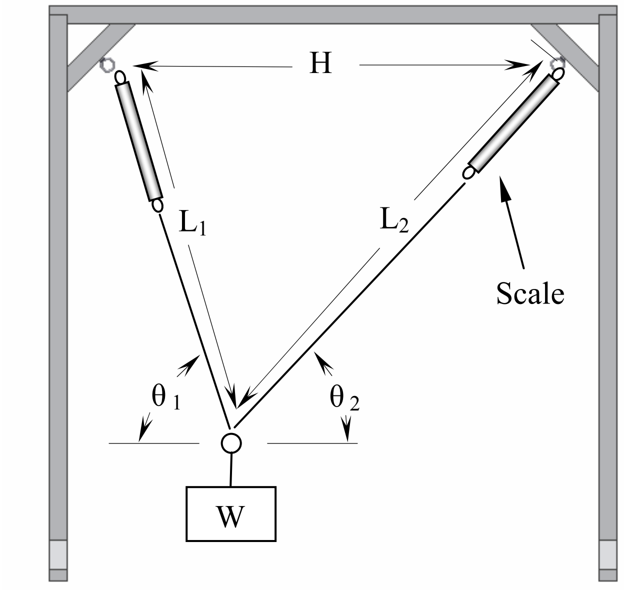

Figure 1: *Basic Components of the Vector Stand*

Procedure

1. Attach the weight to the left most position of the cable system.
2. Measure the tension in cable 1 (T_1), the tension in cable 2 (T_2), L_1, L_2, and H. Record your data into Table 1.
3. Repeat the measurements for the remaining six positions, working from left to right.

Table 1: *Raw Data*

Position	T_1 (lbs)	T_2 (lbs)	L_1 (in)	L_2 (in)	H (in)
1					
2					
3					
4					
5					
6					
7					

Calculations and Data Reduction

1. Determine the angles, θ_1 and θ_2. Show one sample calculation.
2. Determine the y-component of the tension, T_{y1} and T_{y2}. Show one sample calculation.
3. Let $T_{y1} + T_{y2} = T_{ytotal}$. Show one sample calculation.
4. Determine the x-component of the tension, T_{1x} and T_{2x}. Show one sample calculation. (Note: a positive value for tension will be to the right while a negative value will be to the left.
5. Let $T_{x1} + T_{x2} = T_{xtotal}$. Show one sample calculation.
6. Determine the ratio L_1/L_{total}, where $L_{total} = L_1 + L_2$.

Analyses

1. Use Excel to calculate and plot the T_{y1}, T_{y2}, and T_{ytotal} vs. L_1/L_{total} curves on a single graph (graph 1).
2. Use Excel to calculate and plot the T_{x1}, T_{x2}, and T_{xtotal} vs. L_1/L_{total} curves on a single graph (graph 2).

Attach these three graphs to your lab report.

Discussion

1. Draw a free body diagram for the system. Using graph 1 and the FDB, determine the magnitude of the weight.
2. Comment on the values of T_{x1}, T_{x2}, and T_{xtotal} illustrated in graph 2
3. Comment on the sources of experimental error between the measured and theoretical values of weight.