A Learning Tool for Engineering Freshmen
A Model Rocket Project

Daniel H. Suchora, Hazel M. Pierson

Youngstown State University

Introduction

First semester engineering students bring a spectrum of understanding of the engineering profession is. They know that engineers design things and they have been told to be an engineer you need to be good at math and science. Some are very committed to obtaining an engineering degree while others are not too sure if engineering is for them.

Engineering freshmen have taken courses in math and science in high school and generally obtained good grades, but their understanding of these subjects is limited as they try to apply this knowledge to real problems. The same is true of computing. They can manipulate the computer well, but when expected to apply computing solutions to real problems their ability is limited.

In addition many of these students are not well prepared to interact in teams and get along socially with other students. They come from many different high schools and may be the only student coming to our College from their high school. In many instances their first day at class they don't know anyone.

Engineering curriculums in the past basically ignored these facts. The freshmen engineering students had a difficult schedule of math and science courses along with all the social adjustments required in the transition between high school and college. Without a strong commitment to obtaining an engineering degree many capable engineering students changed majors or left school prior to the sophomore year. Also those sophomores who did survive the engineering freshmen year did not have the necessary background and commitment for the rigorous sophomore level engineering courses. At Youngstown State University, as with many engineering schools, a freshmen engineering program was developed and instituted with the goal to improve retention of freshmen engineering students, to better prepare them for the remainder of the engineering curriculum, and to give them a taste of engineering in the freshman year.

First semester engineering freshmen at Youngstown State take a three semester hour course which is taught with two lecture hours and three laboratory hours per week. One of the activities these students complete is a model rocket project. Teams of up to five students investigate the problem of predicting the height a model rocket can obtain and compare this prediction with the actual height achieved by a model rocket launched by the group.

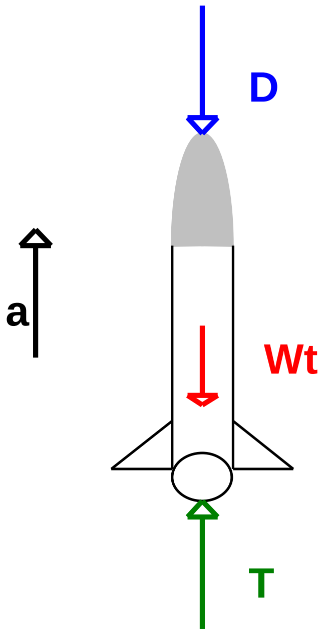
This project has many components which assist the growth of engineering freshmen. First the students are instructed in the dynamics of teams and use the Tuckman model to measure the effectiveness of their particular team. They are exposed to engineering laboratories as they experimentally obtain model rocket engine thrust characteristics. The application of Newton's Second Law to rocket flight provides a good review of this basic principle. In addition, since the equations developed do not lend themselves to a closed form solution, students are introduced to approximations and numerical solutions. Students need to formulate a computer program using MS Excel to solve the problem of predicting the height of the rocket. Finally the students actually build the model rocket, design a method of measuring the height achieved, and field test it to obtain a measured height to compare with the predicted results. The results are analyzed and conclusions reached about the sources of inaccuracy in the entire project.

The model rocket project is one of three major projects completed in the course. It is the second in the sequence and follows a Rube Goldberg design project where teams of students work to design and build a three-minute timer. The third major project involves designing a robot to perform a required task using Lego Mindstorms Kits. The time allotted to the rocket project is about four weeks, but other material is covered while the students are also working on the rocket project. Prior to beginning the rocket project the students have done a series of programming exercises in MS Excel and Mathcad and have been instructed in effective team interactions.

Basic Theory

The students' background for this project is typical of engineering freshmen. Most are taking their first Calculus class concurrently with this course activity. They typically had physics in high school but are not taking physics as yet in college. Their background in math is good but their understanding of physics is at best sketchy. Programming skills are minimal. The goal of this portion of the project is to explain the basics of Newton's Second Law and to develop free body diagrams.

For the most part students think that the sum of forces acting on an object is zero, not mass times acceleration. It takes significant effort with examples to overcome this rather well embedded "fact". One useful example is studying the free fall off a building where an object's weight causes the acceleration of gravity. Another is the example of a person in an elevator standing on a scale to measure the force exerted on the scale by the person when the elevator is accelerating up, down, or moving at constant velocity. Free body diagrams and application of Newton's Second Law to these examples form the basis for the free body diagram of the model rocket in flight shown in figure 1 on the following page.



Where:
D= Drag due to air resistance (a function of velocity)
Wt= Wt $_{rocket}$ **+ Wt** $_{engine}$ (**Wt** $_{rocket}$ is constant;
Wt $_{engine}$ is a function of time)
T= force of engine thrust as a function of time
a= acceleration

Figure 1 – Rocket Free Body Diagram

Applying Newton's Second Law to the system yields

$$\sum F = ma$$

$$[T - Wt - D] = ma$$

Since $m = \frac{Wt}{g}$, where g represents the acceleration due to gravity, the equation becomes:

$$[T - Wt - D] = (\frac{Wt}{g})a$$

Solving this equation for acceleration yields:

$$a = (\frac{g}{Wt})[T - Wt - D] \qquad (1)$$

Equation 1 represents the acceleration of the rocket at any instant of time provided one knows the particular value of each term in the equation at that instant of time. In general all the terms on the right of the equation are functions of time except g, the gravitational constant. For most students this is the first time a problem of this type has been encountered. They are used to quick straightforward solutions where there is an answer, correct to at least 3 decimal points, in the back of the book. The following section shows the development of the engine weight Wt and the trust of the engine T as functions of time.

Experimental Thrust Curve of Engine

Thrust curves of the engines are available from the engine manufacture, but they lack in sufficient detail for use in the project. In addition the large variation in thrust characteristics for individual engines observed in the lab served as good example of experimental uncertainty. Also the use of the engineering laboratories is a definite plus for the freshmen engineering students.

A cantilever beam with a strain gage attached served as the load cell for the project. See Figure 2below. The strain gages were installed by senior level students in another course, but time permitting the strain gages could be installed by the freshmen. The basic theory of stain gages and wheatstone bridge circuit strain indicators was discussed and students were shown how this system could easily be calibrated to read the force applied to the end of the beam. As can be seen in the figure the engine fits in the cylinder at the end of the beam and below that position is an attachment for the calibration weight.

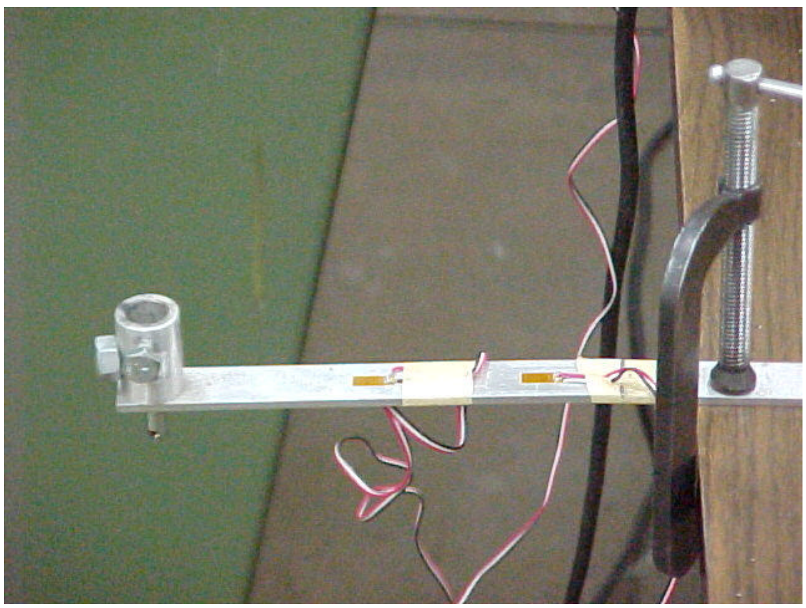


Figure 2 – Cantilever Based Load Cell

For use in this experiment the strain gages were connected to a strain indicator and the output of the strain indicator was input into a SDA 2000 data acquisition system. To calibrate the system a known weight was applied to the end of the cantilever beam and the millivolt output noted. With the system calibrated, the engines could be fired to trigger the system and the trace of force vs. time obtained. Figure 3 shows the system with the engine firing and figure 4 shows the system with the trace of millivolts vs. time for the test engine. The initial signal on the trace is a result of the thrust portion of the rocket burning while the second portion of the trace results from the parachute discharge firing and inducing a vibration into the cantilever beam load cell. The values of the thrust vs. time were recorded along with the time to parachute discharge, which essentially stops the accent of the rocket with a significant downward thrust and increased drag due to parachute deployment.

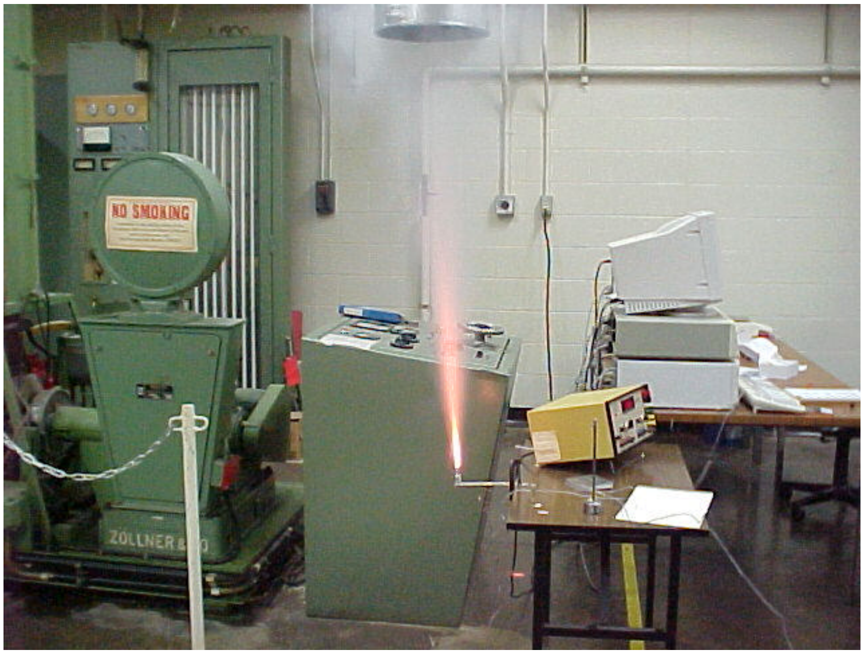


Figure 3 – Engine Firing and Data Acquisition System

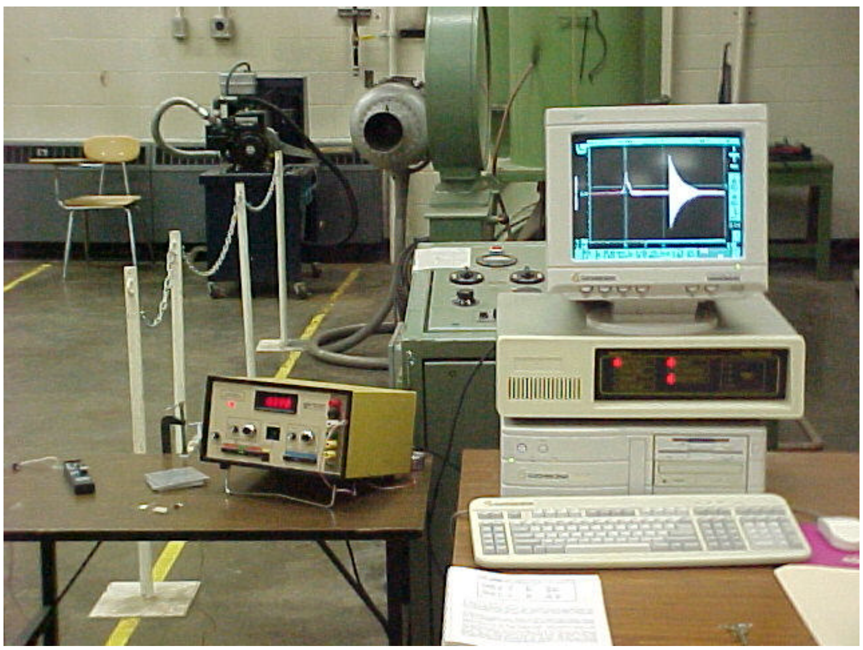


Figure 4 – Experimental Thrust Curve

Engine Weight Function

The total weight of the rocket is the sum of the weight of the rocket plus the weight of the rocket's engine. The weight of the engine decreases as fuel burns, so to get a relationship that prvides the engine weight as a function of time the engine was weighed both before (Wt_{Ei}) and after firing (Wt_{Ef}). Also from the experimental trace of thrust vs. time the duration of firing t_f

was found. By making the assumption that the combustion process causes the engine to lose weight at a constant rate, the weight of the engine can be expressed as a linear function of time:

$$m = \frac{\Delta Wt_E}{\Delta t} = \frac{Wt_{Ef} - Wt_{Ei}}{t_f}$$

Following the relationship for a straight line y = mx+b and noting that b, the vertical intercept is initial value is Wt_{Ei} and that x corresponds to t, the equation for the engine's weight with respect to time can be written as:

$$Wt_E = [(\frac{Wt_{Ef} - Wt_{Ei}}{t_f}) \times t] + Wt_{Ei} \qquad (2)$$

This equation is valid from $t = 0$, to $t = t_f$, noting that t_f is the final time at which the engine is firing. After that, $Wt_E = Wt_{Ef}$.

Drag Force Development

The drag force is given by equation 3 below.

$$D = \frac{1}{2} C_D A \rho \upsilon^2 \qquad (3)$$

Where:
D= Drag Force (lbs)

C_D= dimensionless drag coefficient = 0.75 as given by rocket manufacturer
A= Frontal Area of Rocket = $\frac{\pi d^2}{4}$ where d is the diameter of the rocket body (in^2)
ρ = air density $lb_f\, s^2\, in^{-4}$
υ= velocity of rocket in/s

All the values in this equation are readily available except the air density. To give the students exposure to reading chart values and converting units a psychometric chart was used to obtain this value as a function of outside temperature and humidity. This chart is shown in figure 5 on the following page. The unit conversion required is

$$\rho = [\frac{1}{chartvalue}(\frac{lbm}{ft^3})] \times [\frac{1 \cdot lbf \cdot s^2}{386 in \cdot lbm}] \times [\frac{1 \cdot f^3}{1728 in^3}]$$

FIGURE A-33E
Psychrometric chart at 1 atm total pressure. (From the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA; used with permission.)

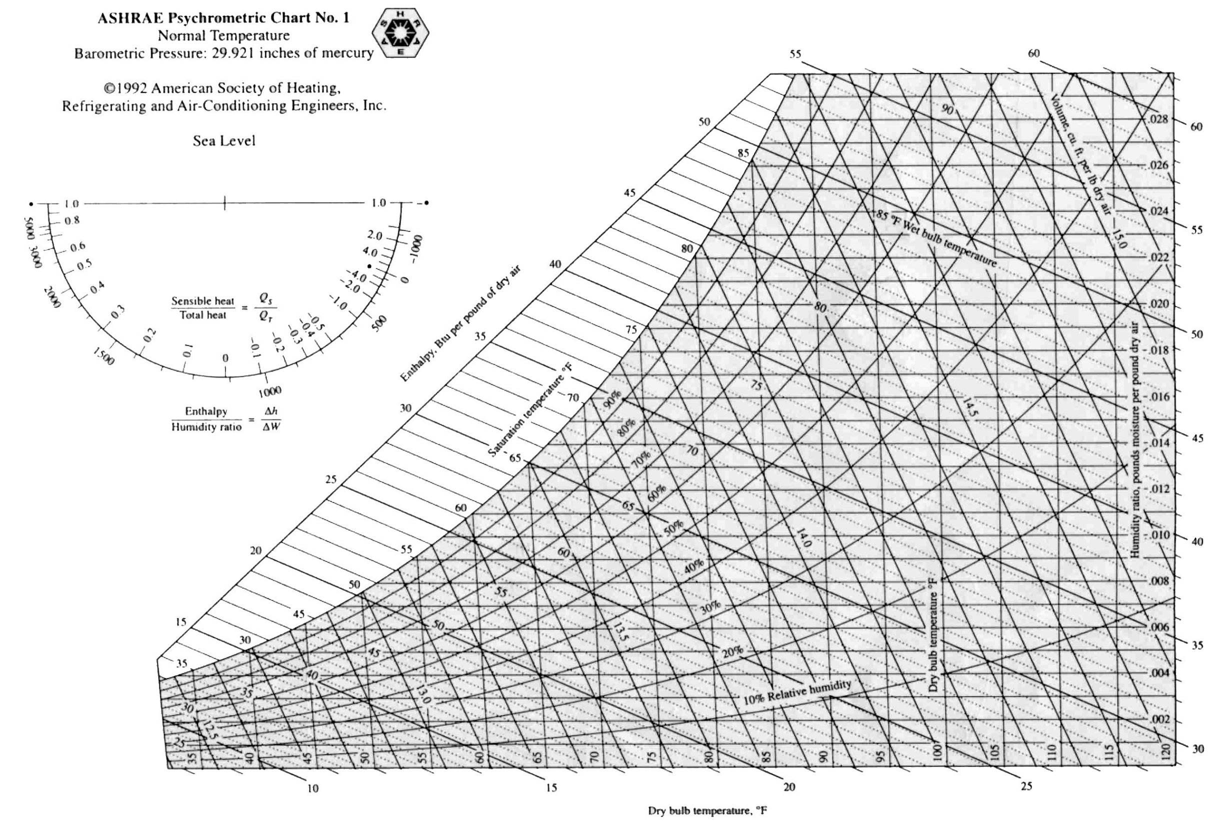


Figure 5 – Psychometric Chart – Air Properties

Excel Program Development

With all this basic background available one can see that equation 1 can be used to calculate the acceleration of the rocket as long as weight, thrust, and drag are know at any instant. Students worked in groups of 4 or 5 to develop the Excel code to solve for the height the rocket achieved. The instructor and lab assistants were available to answer questions, but the students were encouraged to develop the code independently.

Equation 1 gives the acceleration at any instant. Trying to integrate from acceleration to velocity and then finally to height creates numerous problem. First the data obtained for the thrust vs. time does not fit any convenient mathematical form to enable obtaining an equation to represent this data accurately. Also the drag term D is a function of velocity which complicates the analysis even more. Due to these issues it was decided to do a numerical solution based on uniform time step intervals Δt. For our solution a Δt of .02 s was used.

To begin the calculation sequence the acceleration at t=0 was found as

$$a_o = [T_o - Wt_o - D_o](\frac{g}{Wt})$$

Where: a_o, T_o, Wt_o, D_o are the initial conditions for acceleration, thrust, weight, and drag respectively. Note that D_o, the initial drag force is 0 since the initial velocity is 0. Numerically integrating results in the following expressions for velocity.

$$\upsilon_o = 0$$
$$\upsilon_1 = \upsilon_o + (\frac{a_0 + a_1}{2})\Delta t$$
$$\upsilon_2 = \upsilon_1 + (\frac{a_1 + a_2}{2})\Delta t$$

Where: a_2 and a_1 are the incremental acceleration values whose average is taken as a constant over the time interval.

Numerical integration of the velocity yields the following expressions for the height at each time step.

$$h_o = 0$$
$$h_1 = h_o + (\frac{\upsilon_o + \upsilon_1}{2})\Delta t$$
$$h_2 = h_1 + (\frac{\upsilon_1 + \upsilon_2}{2})\Delta t$$

Where: υ_o and υ_1 are the incremental velocity values whose average is taken as a constant over the time interval.

The drag force D in the acceleration presents special problems since it is a function of velocity which is being solved for. As an approximation let $D_o = 0$. Then let D_1 be based on v_o rather than on v_1 which is as yet unknown.

$$D_1 = \frac{1}{2} C_D A \rho \upsilon_0{}^2$$

The equation sequence above is then programmed into MS Excel. From the rocket engine data the students know the thrust at any time and can develop code to predict the height achieved by the rocket until the parachute charge in the engine fires and stops the ascent of the rocket. This is a somewhat difficult task for most of the students. Their background in MS Excel as they enter the course is basically non-existent. The class spends about two 3 hour lab sessions prior to this project learning the basics of MS Excel and doing a sequence of problems. With much effort they can develop the needed code to solve the problem and obtain a graph as shown below.

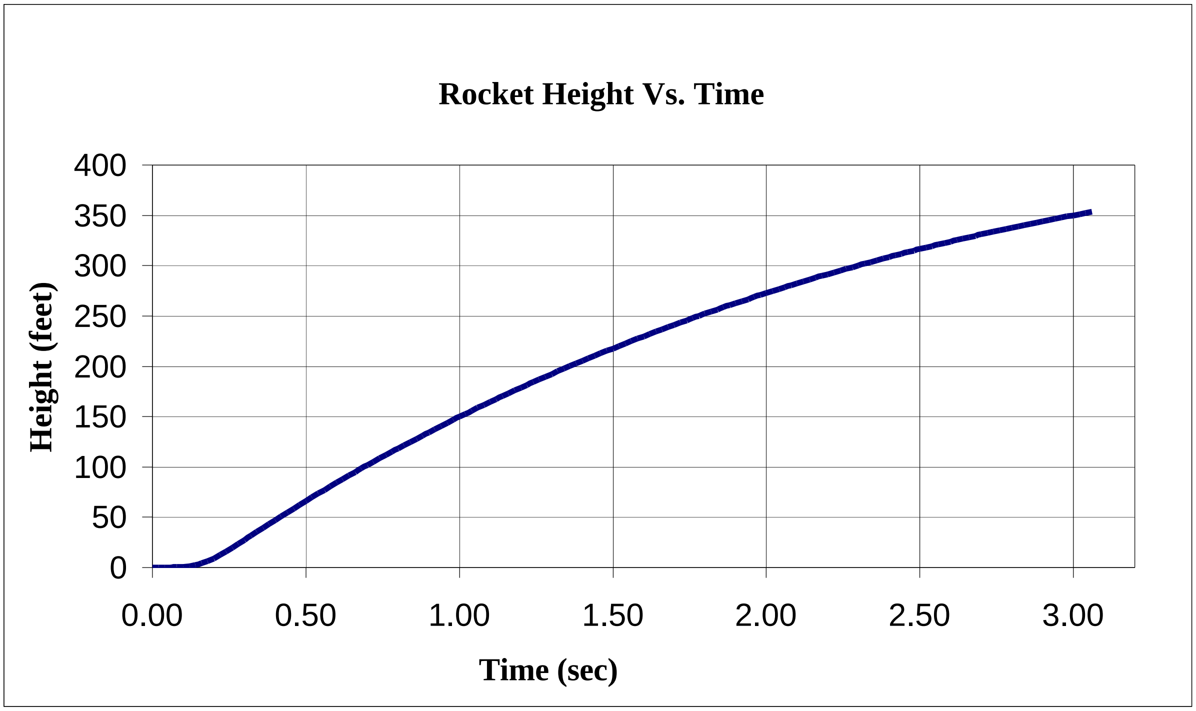
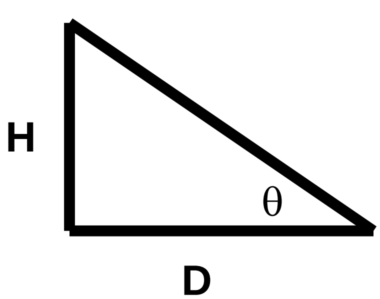


Figure 6 - Rocket Height vs. Time

Rocket Tests

The rockets were tested on the athletic fields on campus. Each student group was responsible for designing a means of measuring the angle of inclination to the highest point of the rocket flight so that right angle trigonometry could be used to find the height achieved by the rocket. The figure below shows the variables involved. The distance D was found using a Bushnell Yardage Pro Compact 600 Laser Range Finder. Each group had to design and build a means of measuring the angle of inclination θ. A typical design is shown in figure 7 on the following page.

D= distance from final position of rocket to person measuring angle
θ= angle of rocket above the ground
H= height of rocket above ground



$$\tan\theta = \frac{opposite}{adjacent} = \frac{H}{D}$$

$$H = D\tan\theta$$

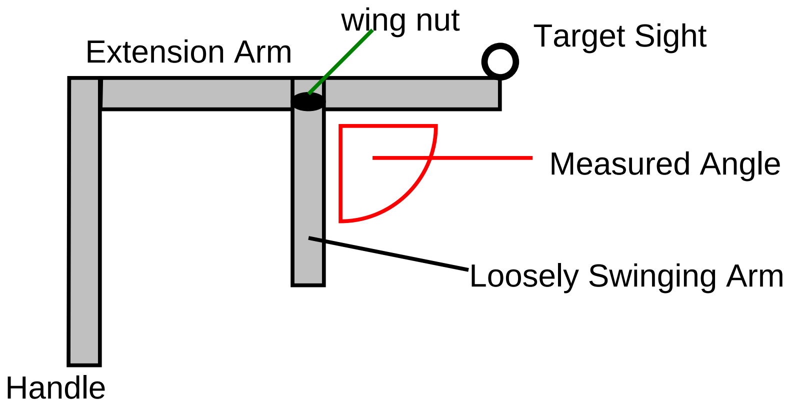


Figure 7 - Typical Design of Angle Measuring Device.

As this device is raised or lowered, while keeping the rocket in the target sight, the swinging arm always points directly toward the ground due to gravity. When the parachute deploys, the person must hold the device in that position and tighten the wing nut with their other hand. The swinging arm is then locked into place. The angle shown in the diagram can then be measured with a protractor to determine the angle of inclination of the rocket.

There are many potential sources of error in trying to determine the height achieved by a rocket. Rarely do the rockets go perfectly vertical and determining the angle of inclination is subject to much error. A diagram used below describes the method used to try and minimize errors.

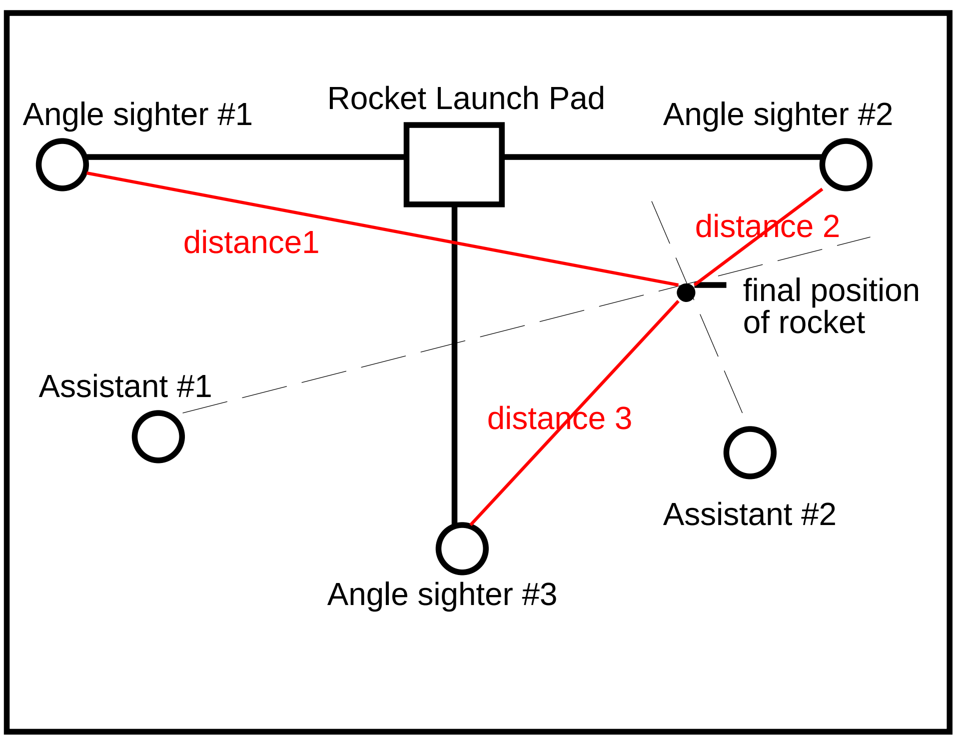


Figure 8 - Launch Field Diagram

Angle sighters 1, 2, and 3 use their angle measuring devices to measure the angle of inclination of the rocket when the parachute charge stops the climb of the rocket and disperses the parachute. Assistants 1 and 2 sight to the rocket at its highest point and walk in that direction. Where their paths cross determines the final vertical position of the rocket. From that position the Laser Range Finder determines distances 1, 2, and 3. With angles measured three different estimates of the rockets height are determined. In most cases there was a rather large variation in results, up to 30% due to difficulty in measuring the angles accurately. Another student would use a stopwatch to determine the time from when the rocket engine ignited until the parachute deployment charge fired which defined the total time to the maximum height position.

Teamwork

Students selected teams of 4 to 5 students to work with on the project. This project was the third in the course where students had already been working in teams and had been instructed in the inter-workings of team members. After working on this project for one week they were given the Tuckman work sheet evaluation and most of the teams were performing at an acceptable level. As a result no further evaluation in team interactions was given.

It was obvious that previous activities in the class had improved the groups' team working skills. Students had formed not only study groups but in many cases had begun to spend time with one another in social settings as well. This project required significant out of class work for the groups and reinforced their teamwork and social skills so necessary for success in engineering.

Conclusions

The model rocket project was a positive growth experience for the freshmen engineering students. First they got to know other engineering students in their group. They used math, science, and computing skills to solve a problem much like many "real" engineering problems. Students worked in the engineering laboratories and worked to collect data accurately. Finally they we required to write an engineering report documenting their work and formulating conclusions from their results. This gave the students a good introduction into what engineering is about and what types of work engineers do.

Shortcomings of the project were mostly due to a lack of time. More time could have been spent on just about all phases of the project, but particularly some of the programming steps used and the basic understanding of Newton's Second Law. It would have been useful to have the groups present their work to the class using MS PowerPoint, but again time was lacking. Overall, however, the students enjoyed the project and the faculty were pleased with the effectiveness of the project at achieving growth and understanding in some of the fundamentals skills required for success in engineering.

Model Rocket Supplies

All the model rocket supplies were obtained directly from Estes Industries. They have an excellent web site at Esteseducator.com which gives valuable resource information. The have an education resource person who can be reached at 800-820-0202 extension 270. Supplies are offered to educational groups at a significant discount to keep costs manageable.

The particular model rocket used in this work was the Gnome using a 1/2A3-2T engine. The launch pad and igniter system was obtained by purchasing a launch kit. This rocket and engine combination gave flight heights of about 300 feet which fit in nicely with the confined space of the athletic fields used to launch the rockets.

DANIEL H. SUCHORA
Dan Suchora is currently a Professor of Mechanical Engineering and Assistant to the Dean at Youngstown State University. He is also the Freshman Engineering Coordinator and Academic Alliance Coordinator. He received his Bachelors and Masters in Mechanical Engineering at Youngstown State (1968, 1970) and his Ph.D. in Mechanical Engineering at Case Western Reserve University in 1973. Dr. Suchora has been at Youngstown State since 1975 and is a Registered Professional Engineer. He is an engineering consultant to local and regional companies specializing in Stress Analysis, especially Computer Aided Finite Element Analysis.

HAZEL M. PIERSON
Hazel Pierson is currently an Instructor of Mechanical Engineering and Freshman Engineering at Youngstown State University. Concurrently, she is finishing dissertation requirements for her PhD at the University of Akron. She received her Bachelors of Science in Mechanical Engineering at the University of Texas at Austin in 1985 and her Masters in Mechanical Engineering at Youngstown State in 1998. She has worked as a materials and process engineer for Packard Electric in Warren, OH and currently offers consulting services to local industries. Her research interest is in the areas of vibrations, rotor dynamics, and advanced stress analysis.