Development of Engineering Problem Solving Skills Through Laboratory Experimentation

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Abstract

This paper describes approaches used to teach and develop various aspects of skills necessary for solving majority of real world engineering problems. The learning takes place during experimentation with a very low cost apparatus for accelerating projectiles. The apparatus utilizes several basic physical principles such as elasticity, gravity, sliding friction, and fluid friction. Various geometric characteristics of the apparatus and the process are used as variables. The apparatus is fairly fool proof, so after a brief introduction, very few guidelines for what to do and how are given to students. However, the students are monitored for progress in accomplishment of their own goals and how they stand compared to another competing group. The learning process includes competition between teams of students who use a given experimentation setup. The problem solving skills targeted in this exercise include approaches traditionally associated with engineering such as math and stat-based analysis, optimization and prediction. Since real world engineering problems are seldom purely technical, the so-called soft skills are also accentuated with heavy emphasis on process organization and teamwork. The goal of the exercise is not only to solve a given problem, which is intentionally not clearly defined, but also to come up with a range of solutions based on the understanding of the underlying scientific principles, and to develop metrics to evaluate these solutions. Stating and solving engineering contradictions present in the design and functioning of the apparatus have proven to be one of the prime areas of students' problems. An initial assessment of areas of biggest problems encountered by students during the course of the whole process is included along with proposed remedies.

1. Introduction

Problem solving skills are the very essence of engineering know-how. It is not only the knowledge of subjects, procedures and the environment an engineer functions in, but also the ability and skills to evaluate a problem and accomplish a task at hand. Several recent publications by professional engineering societies, as well as by academics, illustrate industry expectations for the range of skills possessed by engineering and technology graduates [1, 2, 3]. Some authors stress the need for development of the so-called 'soft skills' as an equally important part of education of a professional who can be regarded as an intellectual possessing deep knowledge in a technical field [4, 5, 6]. Since engineers are "creators of the environment that never was", accomplishment of an engineering task encompasses scientific knowledge and skills of using that knowledge in various economic and human environments. Knowledge of a subject and skills of using the knowledge to accomplish a goal are sometimes viewed as a separate set of abilities [6, 3]. Possessing one of them does not automatically equate to ability of successfully accomplishing a task in a given environment. Both, knowledge and skills must and can be taught; development of skills requires practice [7, 8]. Some academics argue that creativity, probably the most elusive and difficult to teach component of engineering design and engineering practice in general, can be taught [8, 9]. Studies on information gathering by groups of freshmen, senior students, and people twice their age, showed that the amount of practice does make difference in design output [,10, 11].

Bachelors level engineering and technology graduates have 4 years to acquire the technical knowledge and skills in using it. In America, this time has remained unchanged for over 100 years, although it increased over two fold for medical and legal professions. Structured engineering education has evolved into different models from the establishment of Ecole Nationale des Ponts et Chaussées by French king in 1747. The school prepared military engineers for Corps de Ponts et Chaussées established in 1716. Although that education was a somewhat flexible compilation of independent studies, it is widely considered to be the first organized education that differed from the centuries old education model of one master and few apprentices. In 1794 L'Ecole Polytechnique was established to prepare engineering officers for French army and engineers for state service. It is considered to be the first engineering institution with a structured process of knowledge transfer exposing students to various disciplines and points of view. The founders of that institution recognized that with the ever growing body of knowledge needed for a successful engineering career, the then present educational approaches had become largely insufficient. As search for more efficient transfer of engineering knowledge and skills continues, some engineering programs have been almost totally revised to allow room for learning through doing, by creating educational environment that closer reflects real-world engineering practice [12]. Such environment accentuates team projects using laboratory experimentation as a mean for development of skills needed in realization of the projects. Since majority of successful improvement undertakings start with setting a goal, engineering activities are not limited to solving a technical problem; these also encompass explanation of why a particular solution to a problem is the best and implementation of the solution [13, 14].

2. Problem Solving Skills

A general term 'Problem Solving Skills' comprises of many specific skills that are quite universal in nature of their application and are not limited to a technical profession only, but are universal in application. Due to curricular choices and time constraints, not all the skills are developed and practiced in a specific course or even during entire engineering or technology education.

The list below shows 8 problem solving skills (virtually for any profession), which engineering and technology students should develop while attending university.

- describe and understand the problem
- develop goals and plans and establish procedures
- access and manage information
- analyze critically

- conceptualize, design and create solutions
- establish performance metrics
- verify solutions
- communicate

These are the skills targeted by the activities described in this paper. A different outlook at problem solving skills based on cognitive, metacognitive and attitudinal skills needed for problem solving was compiled by Woods [15], and related to personal attitudes.

3. Identification of improvement needs

Through an ongoing self-assessment of two Engineering Technology programs at CCSU: Manufacturing and Mechanical, it became apparent that teaching of some of the above listed skills did not score well on our internal 3-level scale: 1) Development, 2) Practice, 3) Evaluation. The senior level course in manufacturing process planning was chosen for the implementation experiment. It has traditionally covered technical aspects of various manufacturing processes and technical aspects of planning a part making process (a clearly defined technical goal). Based on the author's current experience with industrial projects, several very important aspects of engineering work had to be included in the course to develop some of the skills necessary at most stages of an engineering project.

The project-specific problem solving skills not sufficiently emphasized in the courses leading to the course in Manufacturing Process Planning were the ones dealing with:
- goal setting
- establishment of metrics
- measurement of outcomes
- creation of various technical and business what-if scenarios
- advanced preparation for various outcomes of these scenarios
- development of feel for process variability
- establishment of 'good enough' cutoff metrics for project stoppage or continuation
- establishment of cutoff boundaries for 'too good and too costly'

Other project-specific problem solving skills that were emphasized in different activities of this and other courses, but still could benefit from the experimental project, were:
- project reviews
- communication and documentation of project flow
- graphical presentation of data
- working in an environment of multiple and conflicting views on goals and means of achieving the goals

Out of 12 major weaknesses of engineering graduates and senior students in fields of mechanical, manufacturing and industrial engineering as seen in Central Europe, Western Europe and North America [3], the following have been identified as possible improvement targets in this course:

- lack of skills in defining core of a problem and deciding that a solution is 'good enough'
- avoidance of contradictions in problem solving - drive to optimize existing solutions
- lack of design capability
- preference to work as individuals (little desire to work in teams)
- little project planning skills

3. The experiment

The experimental project attempts to model work environment that: faces a novel problem; works within seemingly well known constraint; believes to possess an adequate body of general problem-related knowledge and problem-specific knowledge; and has a project team whose members have experience in solving similar problems. The project starts with no handout, no advanced preparation. Teams of eight to twelve students are formed. Introduction to the project is intentionally brief, and besides explaining instructional goals and directing the teams to work on ball launching process, few specifics are given about what to do and how.

Figure 1. Experimental setup.

The experimental apparatus shown in Figure 1 is a simple catapult for launching projectiles (golf size balls of different characteristics were used). Students devise their own project goals, auxiliary tools, experimental procedures, performance metrics, ways of evaluating results and assignment of tasks. Due to students' very limited knowledge of statistical procedures and software, as well as time constraints of the course, the statistical analysis of experimental data is done by the instructor. Each team receives results of data analysis for interpretation and decisions on further course of action. An attempt to teach simple experimental design, similar to the one described by Ludlow et al. [16] failed in this course. The failure is believed to be a result of fairly basic statistical knowledge possessed by Engineering Technology students after taking the only statistics course required in the curriculum. According to students' comments, some of the knowledge acquired in this freshman/sophomore level course is used in junior level SPC course only, and largely forgotten by the time of taking the senior level course in Manufacturing Process Planning and Estimating. Teaching of experimental design was consequently substituted by a small presentation based on results of the experiments. Different approaches to DOE using various Fractional Factorial designs were illustrated using experimental results to show their influence on experimental cost, resolution as well as possible shortcomings of such designs. The comparison is described later in section 5 of this paper.

Table 1 shows experimental process output and variables chosen for the experiment by one of the teams, along with the number of settings available on the catapult, and the number of settings chosen for the experiment. The catapult base and the ball landing area were in this experiment on the same level. Table 2 shows choices made by another team, which had ball landing area 30" lower than the catapult base.

Table 1. Experimental process output and inputs (Team #1).

Response name	Response symbol	Response type	Unit			
Horizontal distance of ball flight	R1	Continuous	inch			
Variable name	**Variable symbol**	**Variable type**	**Unit**	**Number of settings used**	**Low level (- or 1)**	**High level (+ or 2)**
Arm pin position	A	Discrete	--	2	1 (bottom)	3
Stop pin position	B	Discrete	--	2	2 (=142°)	3 (=126°)
Forward pin position	C	Discrete	--	2	2	4 (highest)
Ball type	D	Discrete	--	2	Green foam	Bouncy
Arm pullback angle	E	Continuous	deg	2	160°	188°
Distance measurer	F	Discrete	--	2	P	J

Table 2. Experimental process output and inputs (Team #2).

Response name	Response symbol	Response type	Unit			
Horizontal distance of ball flight	R1	Continuous	inch			
Variable name	**Variable symbol**	**Variable type**	**Unit**	**Number of settings used**	**Low level (- or 1)**	**High level (+ or 2)**
Stop pin position	A	Discrete	--	2	4 (=110°)	3 (=126°)
Rubber band type	B	Discrete	--	2	Red, soft	Brown, hard
Arm pin position	C	Discrete	--	2	1 (bottom)	5
Ball type	D	Discrete	--	2	Green plast.	Ping-pong
Forward pin position	E	Discrete	--	2	1 (lowest)	4 (highest)
Arm pullback angle	F	Continuous	deg	2	160°	188°

4. Deliverables

A detailed and organized plan of activities and technical documentation is required before proceeding with the experiment. A good documentation of project activities and decisions related to the investigated process is one of the most important things required from the project team. The documentation must contain information about the following:

1. Project objectives
2. Process variables, constants and constraints
3. Environment variables, constants and constraints
4. Estimated influence of each previously listed variable and constant
5. Estimated ease of setting each listed variable and constant
6. Estimated variability of each listed variable and constant
7. Variables chosen for the experiments
8. Metrics for each variable and constant
9. Levels of each variable to be set as a constant
10. Estimated run time

All decisions and future recommendations that due to time constraints cannot be implemented in class are submitted in writing with specifications about:
Who / How / When / Expected Results

5. Results and analysis

Figure 2 shows one of the plots analyzed by the members of team #1. The plot illustrates that on the average, the second distance measurer (J) reads longer distances than the first one (P). However, the significance of using one or the other distance measurer is extremely low. Minitab GLM procedure output confirms very high significance of all other variables used, the most influential being Arm Pullback Angle (E), followed by Forward Pin Position (C) and Arm Pin Position (A). When asked to specify a dominant physical effect behind the demonstrated behavior of the system, the members of team #1 suggested energy stored in the extended rubber band. Using geometric characteristics of the catapult, they calculated the length of the extended rubber band at pullback point (Le-pb). Figure 3 shows process output plotted versus that new variable. The expected clear trend for horizontal distance of ball flight versus length of the extended rubber band at pullback point (R1 vs. Le-pb) has not materialized. No simple conclusion can be drawn from that plot, suggesting that there are other influential physical phenomena governing the distance of ball flight.

Figure 3 shows plots for the data obtained by team #2. The data was also analyzed as if a Fractional Factorial experiment was run instead of a Full Factorial. The students could clearly see the loss of resolution, the principal shortcoming of experimentation using Fractional Factorial designs. Although the 1/2 FF design mirrors the FF design pretty well, the 1/4 FF design already shows some signs of loosing true picture of less influential (although still significant) variables.

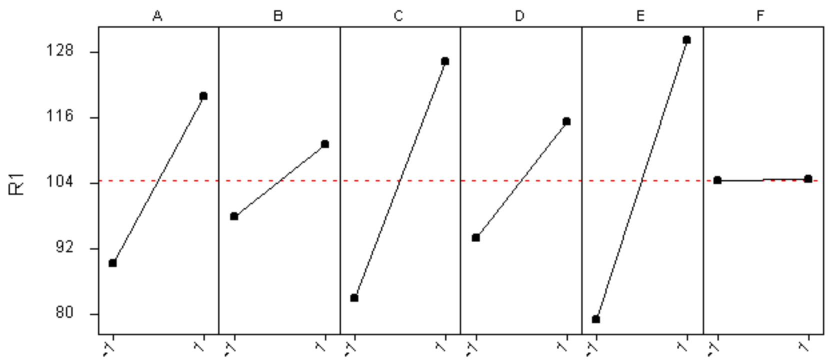

Figure 2. Main effects plot for data means for response R1 (horizontal distance of projectile travel for team #1).

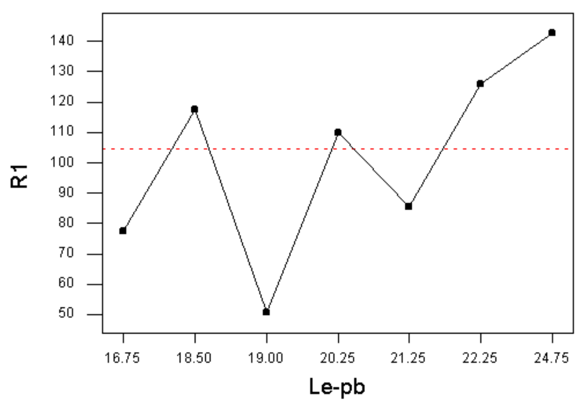

Figure 3. Horizontal distance of ball flight versus the length of the extended rubber band at pullback point (team #1).

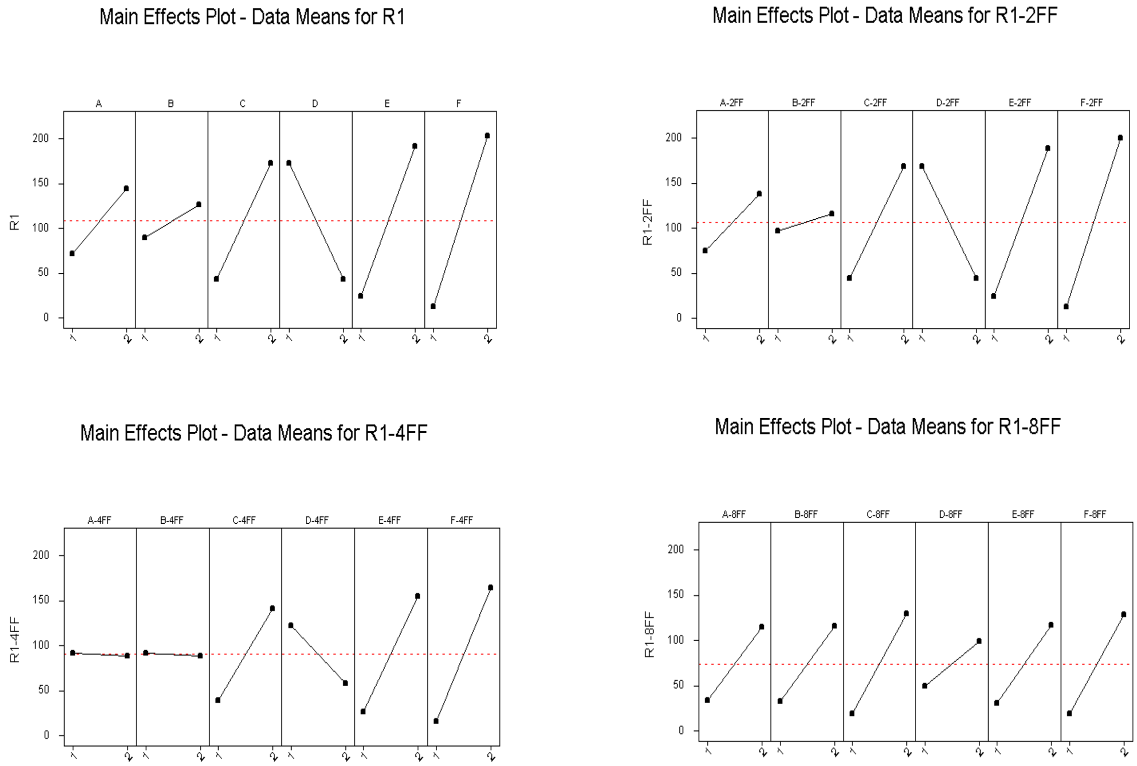

Figure 4. Main effects plot for data means for response R1 (horizontal distance of projectile travel for team #2). (a) for Full Factorial experiment, (b) for 1/2 FF experiment, (c) for 1/4 FF experiment, and (d) for 1/8 FF experiment.

6. Observations and Conclusions

Iterative process of information acquisition, organization of information, statement of activity objectives, planning and carrying out experiments, processing results and decision making for further activities were one of the primary goals of the experimental activities. The experimental experience aimed at giving students possibility of guided practice within loosely defined boundaries. Overall, well known and seemingly simple process of ball launching was easy for students to relate to and did not require up front searching for pertinent information. At the end of the project, most participants agreed that documentation related activities were real time savers.

Out of the major weaknesses of mechanical and manufacturing engineering graduates and seniors (as listed in section 2) only the second one ("Avoidance of contradictions in problem solving - drive to optimize existing solutions") was not addressed successfully. The process used in the project renders itself very well to optimization rather than a thorough redesign.

From the eight project-specific problem solving skills listed in section 3, five were successfully accomplished. The less successful three: 1)"creation of various technical and business what-if scenarios", 2)" advanced preparation for various outcomes of these scenarios" and 3)"establishment of cutoff boundaries for 'too good and too costly'" were given a smaller attention by the students. This was due to time constraints of the class, and, according to students' assessment, due to "a lesser fun with working on them". Students simply did not see the importance of doing anything about these issues, because they seemed to be too detached from the experiment itself.

Due to loosely defined goals of this experimental project, the teams developed efficient internal communication, and with the exception of a few non-contributors fostered good organization of activities. As for the structured planning of activities and evaluation of results, the teams have not seen much value to them, and had to be held back from concluding quickly and moving on.

The incomplete achievement of the above described educational objectives will be addressed in the future runs through a handout given in the course of the project. The handout contains specific what-if scenarios to be addressed, and it specifies a time frame for delivering the results.

Looking at the project from the perspective of extensive experience and findings reported by Woods [15], this very low cost, very versatile project accomplished most of the stated objectives in the development of problem solving skills. Only a few organizational and time constraints existed. Requirements about formal deliverables of the project existed were also limited in number. Although team members felt the burden of their freedom in decision-making and often were confused about what to do next, a vast majority appreciated being in control of their goals and found it motivating.

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