IDEA-Pen: Interactive Design and Analysis through a Pen-based Interface

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Introduction

For students to succeed in engineering design (and engineering practice) they must be able to make design decisions that are grounded in data and analysis. The potential danger, however, in introducing analysis and calculations too early in the design process is that this may lead the designer to become "fixated" on the current design idea and not explore other, potentially better ideas[1, 2]. This can be problematic as engineering education endeavors to teach students to be more innovative. Thus, while it is important to teach students how to support their design decisions with analysis, it is likewise important to help them engage in analysis without leading to limited exploration of alternative ideas. The overarching goal of this project is to provide students with a more coherent and connected experience with learning engineering design and engineering analysis by facilitating the learning of both design and analysis through a natural, intuitive and portable pen-and-tablet-based system, called 'IDEA-Pen'.

The aims of this project are as follows:

1. Enable intuitive creation and manipulation of sketches representing engineering mechanics and kinematics problems, and explore, through critical exploration, structural and kinematic "what-if" scenarios by using finite-element solvers and constraint solvers to run quick simulations.
2. Enable a visual dialogue between the student and teacher, and a collaborative learning environment among students, through easy, intuitive, and real-time exchange of higher level ideas embedded through Sketch-Based Interfaces and Modeling (SBIM).
3. Create a software platform for sketch-based engineering analysis that allows real time exploration of ideas that require deeper computational support, training and contexts not accessible in the past by instructor in a classroom or lab.

We will thus make a critical bridge between the traditional, equation-based "mathematical" learning of engineering, and the "visual", exploratory engineering learning that is more design-oriented.

Use of Technology to Support Engineering Learning

1. Multimedia in the classroom

Over the last decade, engineering classrooms across the country have been augmented with multi-media equipment and modern information technology, dramatically improving the flexibility of classroom presentation media. In spite of the modern changes, traditional chalkboards have yet to be completely replaced. Many instructors still prefer to use the chalkboard or white board to other innovative instructional media. The advent of multimedia with its high quality images, animations, and three-dimensional models has greatly facilitated the illustration of complex concepts where the limited media of chalk- and white-board presentation falls short. However, multimedia can become obtrusive and disrupt the flow of a lecture, ultimately impairing the learning process. Students, too, prefer to take lecture notes or work out homework problems on paper rather than using electronic media. The main motivation for using chalkboard or paper lies in their naturalness, fluidity, and ease of interaction. Writing is dynamic and especially beneficial for situations in which learning-based problem solving involves adopting a step-by step method, such as in statics, mechanics or kinematic analysis.

2. The Rise of Tablets

With the advent of innovative digitizing technologies and multi-touch Tablet PCs (like the iPad and Android tablets), it is now possible to combine the powers of computation with the quick and intuitive feel of 'pen-and-paper' type interaction for educational technology development. Studies have shown that teaching with a Tablet PC enhances the teaching experience and provides greater flexibility for instructors. Moreover, the students become favorably disposed to the use of the technology both inside and outside the classroom[3].

3. Computers and Learning Barriers

Higher-end analysis tools in engineering such as for finite element analysis or kinematic analysis require training and extensive software practice in Windows, Icons, Menus and Pointers (WIMP) environments. There is a clear need and benefit to create systems with interfaces that match real-world problem-solving environments[4]. Some of the recently developed pen-based tools for education in general, include Classroom Presenter[5,6] and Classroom Learning Partner[7], and for

engineering education specifically, include Newton's Pen[4] (a statics tutor), Kirchhoff's Pen[8] (a tool that teaches students to apply Kirchhoff's voltage and current law), and STRAT[9] – for students to learn standard truss analysis.

4. Learning by exploration with pen-and-tablet computers

The affordances provided by the new pen-and-touch-based tablets, by enabling quick and intuitive synthesis and analysis, would trigger new mechanisms of learning by such critical exploration and problem-based learning[10, 11]. Firstly, we plan to explore the new situated learning mechanisms at the interface of design and analysis. Secondly we hypothesize that the nature of questions asked by students in class will increase in quality and quantity. Thirdly, we will develop a platform that can be used in varied mechanical and civil engineering applications where the traditional design to computational analysis gap can be closed thorough a higher level of abstraction of exploratory questions that static text books and toy problems cannot provide. Thus, in contrast to current tools that are proprietary and limited to one application, we leverage our earlier completed research to create a platform for a series of mechanical engineering classroom applications.

Description

Through the IDEA-Pen platform, we intend to explore and inform directions to transform the state of current student-teacher interactions in the classroom and student self-exploration of problems by:

➢ Providing an environment that facilitates the integration of engineering analysis and engineering design by allowing users to explore different design options in early stages even before the detailed designs are made

➢ Stimulating an environment for design-analysis exploration, in which questions like 'what-if', 'why', 'what' and 'how' will be more effectively answered through on-the-fly simulation and visualization.

➢ Allowing better understanding of practical situations through solving problems, where conventional equations do not apply, and also beyond "toy" textbook problems.

➢ Enabling the transition from a model of education that is teacher-centered and passive to one that is student-centered and emphasizes active-learning[12].

- Enabling self- and collaborative learning in students through critical exploration of engineering concepts.
- Enabling easy creation of two-dimensional geometry for different purposes ranging from engineering diagrams to design projects.
- Empowering the student-designers to analyze and explore different concepts for stresses, deformation, material selection and failure during the early stages of design, rather than the conventional way of analyzing after detailed design.
- Positioning our work so that the "app store" infrastructure available in the iOS platform or android platforms can be used in the future to distribute the tool itself. Students with an iPad or Android tablet would be able to directly install the app from the store.

This proposed pen-and-tablet-based tool will have a sketch-based interface where the users can draw and write as they would on paper with minimal constraints imposed on them. For simulation and visualization purpose, this interface would be seamlessly integrated with contemporary Finite Element Analysis (FEA) tools like ANSYS and SIMULIA without the burden to have to learn these complex tools. The rationale behind using FEA is its wide applicability in solving problems in structural, dynamic, thermal, fluid and electrical engineering problems[13, 14, 15], and the ability to demonstrate a wide variety of concepts effectively, for example, applying FEA to a common truss problem can help the student visualize the bending of truss members and deformation in a way previously not possible. Use of FEA for studying engineering concepts is similar to the inclusion of laboratory experiments in lecture-courses, to provide reinforcement of core lecture material more effectively than a textbook[16]. Also, FEA can be used to bridge the gap between traditional learning through textbooks, which are typically comprised of standard geometry, and applying those concepts to real world and design problems with complex geometry, where knowledge gained from textbooks alone is not sufficient. Though powerful with advanced graphics and animation capabilities, these commercial tools do not lend themselves to use in engineering education as they were primarily developed for the industry. Like any traditional WIMP style computer-aided-design (CAD) systems, these tools have a steep learning curve and modeling directly on them is a very tedious process[17]. Hence, to overcome these difficulties and at the same time effectively use their advanced features, the proposed tool will intelligently replace the modeling interface with a pen-based interface providing for natural

interaction. This would potentially enable the users to effectively use the tool even without much knowledge of both the theory and application of FEA. This tool overcomes the primary barrier in the time investment and cognitive capacity needed to learn conventional WIMP-based analysis tools, and provides new opportunities for more students to use engineering analysis to support engineering design decisions. Instead the user can now, for example, focus on the primary concepts in shape synthesis and stress-analysis, as well as motion analysis needed in kinematics situations.

Prior Work

One of the authors has developed a successful research prototype – FEASY (acronym for Finite Element Analysis made Easy), a pen-based interface incorporating finite element analysis for early design[17]. This paper addressed some of the challenges associated with developing pen-based interfaces and evolving them into the computational platform of choice. One of the major requirements is the need for fundamental techniques to transform the informal and ambiguous freehand inputs to more formalized and structured representations. Such a transformation is a crucial step in sketch understanding, for assisting rapid creation and evaluation of new ideas and also in reduction of the total time and effort spent in creating drawings on a computer. This process is termed as *beautification*. Another such challenge is *symbol recognition*, the task of recognizing shapes and symbols.
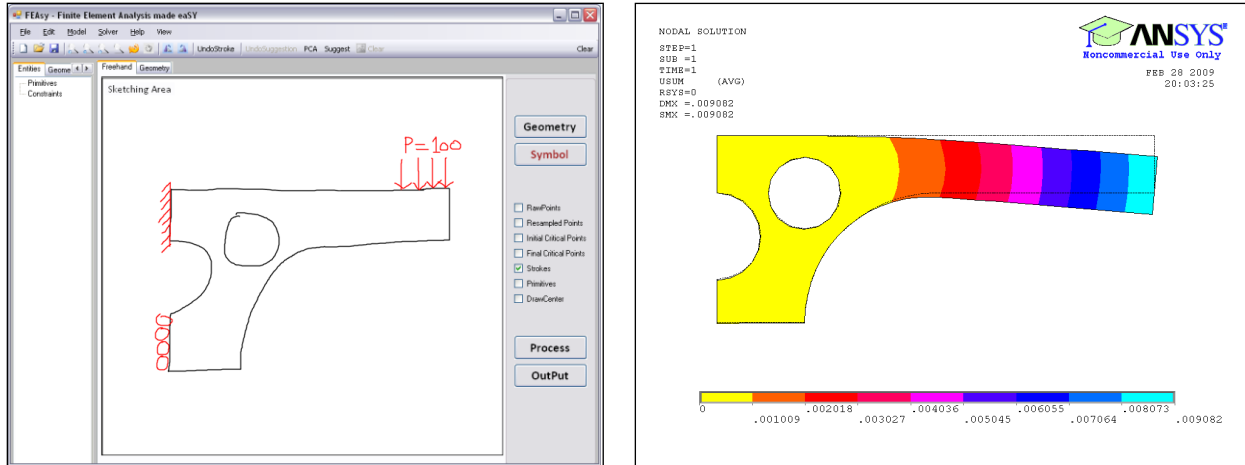
Fig. 1 - The FEASY interface showing a hand-drawn sketch of a 2D bracket (left) and the corresponding deformation results in ANSYS (right).

FEASY incorporates a domain-independent, multi-stroke, multi-primitive beautification method that allows the users to draw in an unrestricted fashion and at the same time robustly copes with the imprecision and variation in freehand input.

FEASY includes a standard set of symbols (Table 1) that would be selected in a separate "boundary condition mode" by the user and applied on the sketched model. The system would then export the model geometry, boundary conditions, loads, material and element description and meshing parameters in a unified data file as a set of commands (like a script) specific to the FEA software. The users can then run this file to get the desired output.

Symbols / Text	Description
	Fully Constrained
	Roller
	Load (force / pressure)
	Moment
	Dimension (Length or Diameter)
	Dimension (Radius)
F, P, T	Force, Pressure, Temperature
=	Equal to
0, 1, 2, 3….9	Numbers (temperature load, dimensions)

Table 1 – Symbol Library for FEASY

Examples

Figure 2 shows an example of a bracket being modeled in FEASY and the deformation results in ANSYS.

Figure 4 shows an example of a two-dimensional cantilever beam with a point-load applied at its end illustrating the sketching process. The user sketches a rectangle with one input stroke in geometry mode (black ink) as shown in Fig. 4(a). The sketch beautified by the system is shown in Fig. 4(b). The user then switches to 'symbol' mode to select the boundary conditions, loads, and dimensions (shown in red). On pressing the 'process' button, the system processes the input and the result is shown in Fig. 4(c). The user selects material properties as required to proceed. The system then exports the input as a set of commands specific to ANSYS shown in Fig. 4(e). The result (displacement vector sum plot) obtained on running this file in ANSYS is shown in Fig. 4(d). This model is an ideal example for students who wish to understand the deflections and stress distributions in an introductory 'Strength of Materials' course.
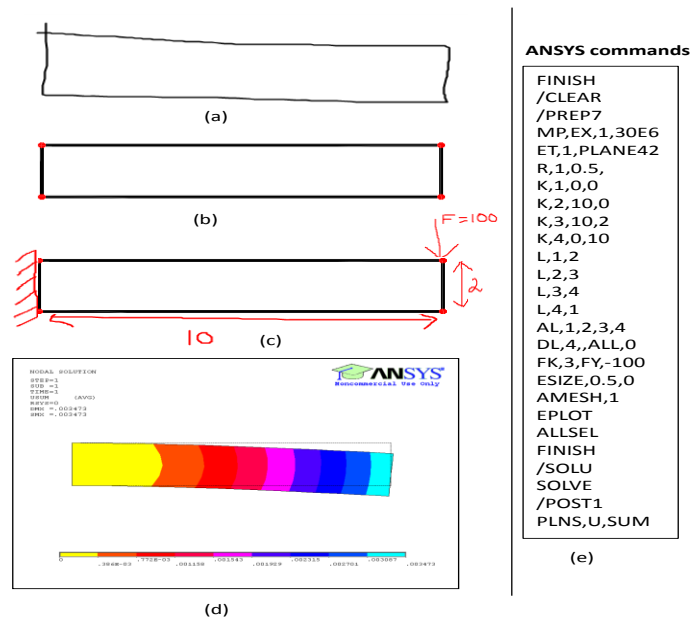

Fig. 2 - Example of a two-dimensional cantilever beam supported by a point load - 100lbs at the end

A preliminary user study was conducted to evaluate the effectiveness of FEASY by porting it on to a Tablet PC running Windows Vista. The testing was done with two teaching assistants and five mechanical engineering senior undergraduate students who were familiar with using ANSYS. The participants were given time to get acquainted with the system and were then asked to analyze the stresses and deformation of examples similar to those shown in Fig. 4. All the participants reported that the system was easy to use in contrast to using ANSYS for the same problem. They liked the idea of drawing geometry with freehand and were very appreciative of the system beautifying the input by inferring the constraints automatically and satisfying them simultaneously without the need for manually specifying them.

Objectives

The project described in this paper is in its early stages. As the project progresses, we endeavor to accomplish three major objectives that will promote engineering design learning through the use of a sketch-based tool that will allow students to engage in engineering analysis while still exploring alternative design activities. Through this project, we plan to:

1. Adapt and enhance a completed research prototype of a natural and an easy-to-use pen-and-tablet-based tool for mechanical and civil engineering education incorporating finite element analysis and kinematics

2. Introduce the tool in one mechanical engineering course (ME444 – Computer – Aided Design and Rapid Prototyping) and evaluate its impacts.

3. Enhance engineering education by introducing the new tool in other areas of the ME undergraduate curriculum and disseminate the tool to the larger academic community (including other engineering disciplines) through web platforms.

We hypothesize that our tool will aid the student in learning finite-element analysis and mechanics of materials from an application-oriented approach. The quick sketching and analysis will aid exploration and deep learning more than the commercially available software.

Integrated Educational and Technical Research

The project represents an integrated research and application effort; technical research, usability studies, educational implementation and educational research efforts are woven together, promoting a model of integrated engineering education research. Research in the form of usability studies will be conducted to ensure that the IDEA-Pen tool is successful in supporting learners' and instructors' education, design and computation needs. It is a foremost concern that the tool is a support, and not an obstacle for either instructors or learners, and that it will enhance learning in the classroom. Our goal is to prove this key hypothesis and iteratively improve the tool and platform. Through this study, we are interested in identifying the extent to which teachers and students accept the tool, and determine what proportion of the acceptance can be attributed to various characteristics of the model. A survey tool will be used and the responses to each question will be based on a 5 or 7 point Likert scale. The questions in the survey will be related to the nine variables – performance expectancy, effort expectancy, attitude towards using pen-based tool, social influence, facilitating conditions, self-efficacy, anxiety, and behavior intent.

In addition to ensuring the basic functionality of the tool, we will conduct a series of studies to further characterize the impact that the tool has on instructor practices, student learning and classroom dynamics. The methods we propose to use include:

1) Classroom Observations

2) Analysis of Student Work

3) Interviews with Students

Table 2 presents a summary of how the survey and these other three approaches will be used to investigate whether and how proposed outcomes are met.

1) **Classroom Observations:** In order to examine the impact of the tool on instructor practices as well as classroom dynamics, we will conduct observations of classrooms during the first semester when the tool is only used by the instructor and then in the second semester when we are able to test the two different conditions: class A where the tool is not used (to collect

baseline data) and class B where the tool is fully implemented in the classroom. In each of these three cases, the same course will be taught by the same instructor. Data that will be collected includes number and type of question asked by student, instructor practices (e.g. amount of time spent on individual topics; number of questions posed to students), and balance between instructor-centeredness vs. student-centeredness (e.g. amount of time instructor is speaking, amount of time students are speaking, amount of time students are given to work through exercises).

2) **Analysis of Student Work:** For each of the classes that are observed, we will also collect copies of student work to investigate students' understanding of the course material, types of mistakes that students make when the tool is or is not used, and to investigate students' design behavior. The specific types of work that we will analyze include copies of students' design reports as well as homework documents (all student work will be de-identified, and we will ensure that this analysis is done under the approval of our IRB). For assessing the impact on creative problem solving, we will use a similar strategy as Robertson and Radcliffe[18] by considering four mechanisms namely, enhanced visualization, circumscribed thinking, premature design fixation and bounded ideation.

3) **Interviews with Students:** Students will be interviewed to characterize the basic usability of the tool, but also to investigate students' other experiences with the tool. In particular, students will be interviewed regarding their experiences with and interest in using the tool outside of class for self-tutoring.

Outcomes	What the tool will do to accomplish this	How will it be measured
An easy-to-use tool suitable for both the instructors and students for a variety of applications	Enable easy creation of two-dimensional geometry for different purposes ranging from engineering diagrams to design projects.	Surveys of instructors and students; interviews with students
Undergraduate students, who have acquired the expertise to use finite element analysis in understanding standard engineering problems	Allow better understanding of practical situations through solving problems, where conventional equations do not apply, and also those that are not listed in textbooks.	Interviews with students; analysis of student work
	Act as a self-tutor for engineering students.	Interviews with students
Senior students, who have gained technical expertise in performing analyses in the early stages of design	Empower the student-designers to analyze and explore different concepts for stresses, deformation, material selection and failure, and kinematic analyses during the early stages of design, instead of the conventional method of using these analyses for verification	Classroom observations; analysis of student work
A framework for instructors, which will enable them to communicate engineering concepts more effectively and efficiently.	Stimulate a more dynamic environment, in which questions like 'what-if', 'why', 'what' and 'how' will be more effectively answered through on-the-fly simulation and visualization	Classroom observations
A model of an engineering classroom that fosters increased student-instructor interaction and makes learning more student-centered.	Enable the transition from a model of teacher-centered and passive-learnin to a student-centered and active-learning model of education.	Classroom observations
	Promote collaborative and cooperative learning.	Classroom observations

Table 2 - Summary of how outcomes will be addressed and assessed

Broader Impacts

The project described in this paper endeavors to impact undergraduate engineering education broadly. The project:

➢ Bridges a critical gap between 'engineering design' and 'design engineering' by enabling users to study their design behavior and to explore different design options at an early stage, even before the detailed designs are made. In the future, students and graduates will have the capability to design better and innovative products and reason collaboratively at higher levels in the conceptual stages. We hypothesize the nature and type of question asking by the students to the instructor will change.

➢ IDEA-Pen also aims to improve engineering learning by providing students (especially in Mechanical and Civil Engineering disciplines) with a natural and an intuitive interface to

learn and explore a wide variety of engineering concepts across the curriculum through real-time simulation and visualization.

➢ Finally, the tool is designed to impact the conversations in the classroom of today, stimulating a more dynamic environment by increasing active student participation and teacher-student interactions, and quality of in-class demonstrations. This can potentially change some of the pedagogical principles followed in the classroom today and also enable the transition from a teacher-centered to a student-centered model of education.

Conclusion

In this paper, we described IDEA-Pen, a portable pen and tablet based system that aims to provide students with a more coherent and connected experience with learning engineering design and engineering analysis by facilitating the learning of both design and analysis. The tool to facilitate the system is in the initial stages of its development. We propose to conduct surveys that are exhaustive and extensive in nature in order to make our system address existing problems faced by students in learning engineering design and engineering analysis and to make it achieve the goal of simplifying the design exploration process.

Acknowledgements

Bibliography

1. Jansson, David G., and Steven M. Smith. "Design fixation." *Design Studies* 12.1 (1991): 3-11.

2. Ullman, David G., Thomas G. Dietterich, and Larry A. Stauffer. "A Model of the Mechanical Design Process Based on Empirical Data." *AI EDAM* 2.1 (1988): 33-52.

3. Adams, Nadine, and Clinton Hayes. "Does teaching with a Tablet PC enhance the teaching experience and provide greater flexibility?" *Australasian Tablets in Education Conference (ATiEC)*. 2009.

4. Lee, Wee San, et al. "Newton's Pen: A Pen-Based Tutoring System for Statics." *Computers & Graphics* 32.5 (2008): 511-524.

5. Anderson, Richard, Luke McDowell, and Beth Simon. "Use of Classroom Presenter in Engineering Courses." *Frontiers in Education, 2005. FIE'05. Proceedings of 35th Annual Conference*. IEEE, 2005.

6. Dyknow Vision (2009), http://www.dyknow.com/ as accessed on January 3, 2013

7. Koile, Kimberle, et al. "Supporting Pen-Based Classroom Interaction: New Findings and Functionality for Classroom Learning Partner." *Pen-Based Learning Technologies, 2007. PLT 2007. First International Workshop on*. IEEE, 2007.

8. De Silva, Ruwanee, et al. "Kirchhoff's Pen: A Pen-Based Circuit Analysis Tutor." *Proceedings of the 4th Eurographics workshop on Sketch-based interfaces and modeling*. ACM, 2007

9. Peschel, Joshua M., and Tracy Anne Hammond. "STRAT: A Sketched-Truss Recognition and Analysis Tool." *DMS*. 2008.

10. Kolodner, Janet L. "Facilitating the Learning of Design Practices: Lessons Learned from an Inquiry into Science Education." *Journal of Industrial Teacher Education* 39.3 (2002).

11. Kolodner, Janet L., et al. "Problem-Based Learning Meets Case-Based Reasoning in the Middle-School Science Classroom: Putting Learning by Design (tm) into Practice." *The Journal of the Learning Sciences* 12.4 (2003): 495-547.

12. Bonwell, Charles C., and James A. Eison. "Active learning: Creating excitement in the classroom." *Washington, DC: School of Education and Human Development,* George Washington University, 1991.

13. Coyle, Marshall F., and Christal G. Keel. "Teaching Finite Element Analysis to Second Year Students." *2001 ASEE Annual Conference & Exposition: Peppers, Papers, Pueblos, and Professors*. 2001.

14. Steif, Paul S., and Edward Gallagher. "Transitioning Students to Finite Element Analysis and Improving Learning in Basic Courses." *Frontiers in Education, 2004. FIE 2004. 34th Annual*. IEEE, 2004.

15. Jolley, W. O., J. J. Rencis, and H. T. Grandin Jr. "A Module for Teaching Fundamentals of Finite Element Theory and Practice Using Elementary Mechanics of Materials." *Mechanics Division, CD-ROM Proceedings of the 2003 American Society of Engineering Education (ASEE) Annual Conference and Exposition, Nashville, TN*. 2003.

16. Baker, J., Capece, V., & Lee, R. (2001). "Integration of Finite Element Software in Undergraduate Engineering Courses." *In Proceedings of the 2001 American Society for Engineering Education Annual Conference & Exposition.*

17. Murugappan, Sundar, and Karthik Ramani. "FEASY: A Sketch-Based Interface Integrating Structural Analysis in Early Design." *ASME Design Engineering Technical Conferences, Computers and Information Science in Engineering*, 2009.

18. Robertson, B. F., and D. F. Radcliffe. "Impact of CAD Tools on Creative Problem Solving in Engineering Design." *Computer-Aided Design* 41.3 (2009): 136-146.