AC 2009-514: INTEGRATING A REVERSE ENGINEERING PROJECT IN A LABORATORY-BASED INTRODUCTORY ENGINEERING COURSE

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Integrating Reverse Engineering Project in a Laboratory Based Introductory Engineering Course

Abstract

Rapid Prototyping technologies has made significant inroads in a number of manufacturing sectors over the last two decades because of ease of customization and quick turn around of concepts to prototypes. The process requires A CAD model developed from the design data as an input which may not always be available. Introduction of affordable 3D scanners has provided the opportunity of developing a 3D surface or parametric CAD model from scanned data by a reverse engineering software. The original design can be further extended when the model is exported to a conventional CAD software. Reverse engineering capability established in Albany State University with the acquisition of a pair of scanners and software during past two years along with an existing 3D Printer has allowed the introduction of a new project in the laboratory component of the introductory engineering course for sophomore level students in the fall 2008 semester. The details of the project along with the results obtained and students' perceptions are discussed here.

Introduction

The introduction of Rapid Prototyping (RP) Technology over two decades ago, has influenced the manufacturing industry significantly reducing turn around time to test various concepts in form and fit checking, improving product tolerance and functional testing, better marketing presentation as well as net shape manufacturing in a large number of fields such as medical and electronic devices, sports equipment and industrial products. Though various RP technologies[1] differ in choice of materials and process as in cost and durability, all of them significantly shorten the time to bring new products to market. In recent years, engineers have also started to use the flexibility of RP technologies in extending the original part design by various software tools which has come to be known as Reverse Engineering. As this new technology has started to influence different field of manufacturing from cataloging of archeological objects to one of a kind or obsolete parts, it is thought to be necessary to expose engineering students in their early years of education to RP and reverse engineering. After a detailed assessment[2] of affordable hardware and software tools currently available, a new fully functional reverse engineering facility has been established and the first laboratory project has been added to the introductory engineering course at Albany State University (ASU) in the fall 2008 semester.

Rapid Prototyping / 3D Scanning / Reverse Engineering

Collectively RP is used to indicate the additive manufacturing processes where the part is made by depositing or sintering layers of thermoplastic resin by a laser beam driven by the part's solid model definition generated by CAD software as the part evolves from the bottom up. From introduction of the first RP machine, SLA -1 by 3D Systems in 1987, various other machines have been manufactured by different vendors based on Stereolithography, Selective Laser Sintering, Fused Deposition Modeling, and Powder Binder Printing. A new class of RP machines known as 3D Printers first introduced by Z-Corporation in 1996 based on Powder Binder method

became a welcome addition because of their small footprint, adaptability to work in an office environment and low cost. Stratasys and 3D Systems followed with their version of 3D Printer.

All RP technologies need a CAD model which is normally developed in commercial CAD software such as SolidWorks, SolidEdge, AutoCAD Inventor, Pro-Engineer from the available design data. In general RP systems use the CAD model generated in STL (stereolithography) file format to drive the laser tool in its path. STL is a neutral file format designed such that any CAD system can feed data to any RP system. As such STL is one of the preferred file formats among all the software tools used in RP, 3D scanning and reverse engineering.

When the dimensional data is readily available a CAD model can be developed for building the prototype in a RP machine. However, for obsolete parts, one of a kind object, or object with an organic form the geometrical data may by generated by recording the coordinates on the surface of the object by a Coordinate Measuring Machine[3] which is time intensive and prone to measurement errors. With the availability of affordable 3D scanners, the geometrical data can easily be recorded by scanning the object with a laser beam multiple times from different angles and subsequently aligning them with a software to create an exact copy of the original part in the computer in a variety of file format no matter how complex the surface geometry may be. A large number of 3D scanners are available today for various applications with varying degree of accuracy and widely differing in cost.

Reverse engineering may be defined as the process of taking the finished product and reconstructing the design data in a format from which new part or mold can be produced. The steps in a reverse engineering process constitute of obtaining and analyzing the dimensional data, creating the CAD model and transforming it into a prototype that can be checked against the dimensional and functional requirements as well as extending the design for new applications.

When a 3D scanner is used to generate the dimensional data, the steps in a reverse engineering project may be summarized as:
- Obtain multiple scans of the part from different angles with overlapping features
- Align and merge the scans to form one whole solid object defined in point cloud
- Refine and process the data further to fill the holes and patch any irregularity in the surface to make a complete, watertight STL file
- Fit a surface through the scanned part data to create a NURBS model
- Create parametric solid/surface model and transfer that to SolidWorks or another CAD software such that the original part geometry can be extended to create new model

Hardware and Software Tools

RP was first established in ASU with the purchase of a 3D printer from Stratasys[4] and SolidWorks CAD software in 2003 which ever since have been used in support of the Engineering Graphics course as well as Engineering Workshops for high school students. When the decision of

extending the well established RP facility to a fully functional reverse engineering facility was made, an extensive search[2] for all the affordable (under $10,000) 3D scanners and reverse engineering software was undertaken around 2006-2007. The first system was acquired in the summer of 2007 in the form of E-Scan scanner and LeiosMesh software and next one in the summer of 2008 in the form of NextEngine scanner and RapidWorks software. The following description refers to the equipment mentioned above.

E-Scan[5] from 3D Digital Corp.

Introduced in 2007 it is positioned at the lower end of the price spectrum but provides better resolution of the part than comparably priced scanners. Laser beam sweeps over the stationary object to obtain the point cloud data. 3d Shape supplied software, SLIM aligns, merges, fill holes and remove noise to form the 3D model that can be exported in many formats including STL. Manual editing of the unwanted data is necessary that may pose a challenge for beginning level users. There is no set limitation of the object size though 8" to 10" in length may be ideal. Also, time to scan an object is significantly shorter making it possible to scan live objects. The price for E-Scan with SLIM software for educational institutions is $5000 which is quite attractive.

NextEngine[6] from NextEngine Inc.
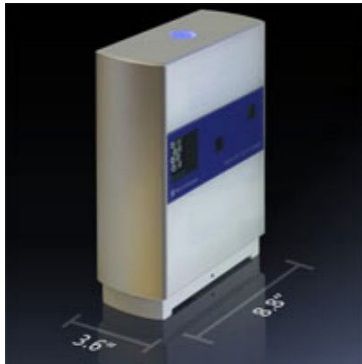
It is probably the least expensive scanner available today with a very small footprint. It captures the 3D object in full color with multilaser precision. Object size can vary from 6" to 10". ScanStudio Core software supplied free with the scanner scans, aligns, polishes and merges the point cloud data to form the model than can be exported in many formats including STL. The scanner comes with an accessory to hold the object upright and in the bracket or 360^0 mode, automatically turns the objects to scan different views. Educational price for this scanner is only $2295 making it quite affordable. Also, RapidWorks reverse engineering software specifically tailored to work with NextEngine scanner is available for $1995 for educational institutions.

LeiosMesh[7] from EGS

The software imports the point cloud data obtained with the 3D scanners or touch probes and transforms that into mathematical meshes or NURBS. Models can also be created using builtin parametric modeling tools. Extensive editing or curves and meshes makes model refinement possible including noise cleaning, smoothening plane surfaces or fitting a perfect cylinder over a curved surface, bridging mesh gaps and mesh hole filling. Model history is displayed in a tree like structure much like SolidWorks. Most popular formats are supported including STL. Single user price for educational institution is $800.

RapidWorks[8] from RapidForm

This powerful software performs all the steps outlined earlier that is necessary to complete a reverse engineering project from scanning the part, cleaning the scanned data, aligning/merging

the scans, patching up holes and fixing irregularities, aligning to a set of coordinate axes, creating a NURBS surface model and exporting to SolidWorks as a parametric solid or surface model where it can be further extended by the normal tools available in SolidWorks. The original software can import or export in all popular formats including STL though the version sold with NextEngine is customized to work only for that scanner. This is arguably the best and most software for reverse engineering and as such relatively complex requiring significant amount of initial training. This is also the most expensive software with a price of $20,000 per seat for industrial users. For educational institutions, a 30 seat floating license is available for $10,000. As mentioned, the NextEngine version is considerably less expensive.

Transfer Engineering Program at Albany State University

ASU conducts a transfer engineering program[9] in the form of Regents Engineering Transfer Program (2+2) and Dual Degree Program (3+2) where students can transfer to Georgia Institute of Technology, state's only public university offering four year degree in engineering, under a cooperative agreement. ASU students complete the core courses in humanities, science and mathematics as well as some freshman and sophomore level engineering courses such as Engineering Graphics, Engineering Computing, Introduction to Engineering Materials, Electric Circuits, Engineering Statics etc. in order to have a seamless transfer to junior level at Georgia Tech. Though the program was primarily designed for transfer to Georgia Tech only, in the past students have matriculated to various other engineering universities to complete their engineering degree program. Even though only a handful of students transfer to Georgia Tech each year, the rate of success enjoyed by ASU students is comparable to other larger universities in the state.

Introductory Engineering Course and Current Laboratory Projects

ASU students are required to enroll in a sophomore level introductory engineering course called "Principles of Engineering Analysis and Design" which is a prerequisite to all the 2000 level engineering courses and as such treated as a gatekeeping course for the engineering program. The course is taught in the third semester with Pre-calculus as the prerequisite. This course is comparable to any other "Introduction to Engineering" course taught in virtually every engineering program and covers such topics as career opportunities, survival skills, team work, communications, ethical practices. Our course also reinforce the concepts learned in Algebra and Pre-calculus with brief exposure to differentiation and integration, linear algebra, complex variables and application oriented problem solving in thermodynamics, electric circuits, statics, economics etc.

But the main difference of this course with similar courses taught elsewhere is the laboratory component[10] where students are required to perform a number of projects. The laboratory was established in 2001 from the funding received from the Department of Education with an intent to provide more realism and familiarity with the current manufacturing and testing equipment at an early stage of students education. The laboratory facility is described in detail in the University website: (www.asurams.edu/coshp/naturalsciences/engineering/facilities.htm). The laboratory comprises of a set of Lego RoboLab and NXT programmable robots, a CNC lathe, a computer controlled Wind Tunnel, a Universal Testing Machine, a metallurgical microscope, a 3D Printer

and MATLAB and SolidWorks CAD software. As is evident from the list of equipment, the goal of this effort is to provide students with realistic and engaging learning experience by making them perform a wide variety of projects and in the process challenge themselves to engage in critical thinking in the underlying hypothesis of those projects. Not all of the equipment and software are used in this course. In general students perform about 8 to 10 projects in a semester in Lego NXT robots, CNC lathe, Wind Tunnel, SolidWorks and 3D Printer. The UTM and microscope are used in Engineering Materials and MATLAB software is used in Engineering Computing course.

**Projects in 3D Scanning and Reverse Engineering**

After the initial break-in period that is normal with any new software or hardware, the first completed project with the E-Scan 3D scanner, SLIM and LeiosMesh software was the reconstruction of a clay model of an icon with organic pattern which was about 8"x 8" in size. A total of eight scans were taken in building the model with hardly any irregularity other than a few small holes which were quickly patched up by LeiosMesh. The model was also printed in the 3D printer.

Figure 1. 3D model of the clay icon

A few more parts were successfully scanned and computer models generated with E-Scan system. The first part with geometric configuration scanned was a bracket. In this case significant amount of missing data during scanning had to be regenerated using LeiosMesh after aligning and merging the initial scans.

Figure 2. Original and 3D model of the bracket. Note large patch of missing data before repairing with LeiosMesh
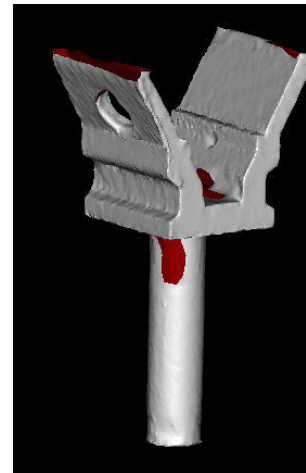
Since the acquisition of the NextEngine 3D scanner and RapidWorks software last summer a number of projects have been attempted. The earliest and most noteworthy of these projects that resulted in successful transition from scanned data to parametric model in SolidWorks has been shown in detail here. The first row shows, from the left, the scanned and aligned model obtained by scanning the face of one of our engineering students in full color and texture, next one shows individual scans that were used in multicolor and the last one is the NURBS surface model. The second row shows, from the left, the addition of the back plate after the model has been transferred to SolidWorks and the prototype made in the 3D printer.

Figure 3. Workflow of the facescan reverse engineering project

Once the procedural steps of this project was established early in the fall 2008 semester, it was decided to be an exciting yet challenging introductory project for our students into the field of 3D scanning and reverse engineering. Students were divided into six two member teams, half of them were assigned to work with E-Scan / LeiosMesh and the other half in NextEngine / RapidWorks. The project assignment was to scan one team member's face by the other multiple times and then cleaning/merging/aligning the scans to develop the 3D computer definition of the face and subsequently generate a plane at the back to create a watertight model. Additionally, students working with RapidWorks/ SolidWorks were expected to create a back plate for the model in the SolidWorks. Each team was given separate instructions of how to use the equipment and software. A detailed manual for E-Scan, SLIM and LeiosMesh was already available. However, though there is a manual available for NextEngine scanner, no written instruction for using RapidWorks software exists. A short list of instructions specifically oriented to complete this project was being developed at that time which has not yet been field tested. This fact was reflected in negative feedback from students at the end of the semester who had to use the NextEngine/RapidWorks system. One of the students in the class was trained in this system at the beginning of the semester and acted as a lab assistant helping others getting familiar with the equipment and software. Students' had to schedule time outside the regular lab class hours because of the extended nature of this project. However, there was no scheduling conflict reported, perhaps because of the small size of the class consisting of only 12 students.

Lessons Learned

The project proved to be extremely exciting to our students from the very beginning though it was assigned at the end of a series of other quite interesting and challenging projects. They worked hard to get as many scans as possible from different angles to recreate a complete 3D solid model of the head. However, the following problems were encountered:

- As good scanned image is crucially dependent on the correct distance, initially many scans resulted in having large gaps for lack of data which is hard to fill without taking more scans. These caused some frustration among the students as they had to repeat their work.
- It was also clear from the beginning that the human hair does not create good images consistently from the reflection of laser rays. Hence, students have to be satisfied with taking only the scans of the face of their partners instead of the whole head.
- Ripples appeared in the scanned images as it was hard to seat still for a minute or more required to take the scan. The problem was somewhat alleviated by switching to quick scan mode.
- Alignment of the scans was a chore for the novice users.
- Lack of a written manual for the RapidWorks software caused some concern though the student assistant could offer immediate help when available.

In view of these problems, the future project assignment needs to be tailored for beginning level users so that the project can be completed without repeating any of the steps.

Results Obtained

In spite of all of the above problems, all the six groups completed their projects on time and submitted written report as was the requirement of the laboratory projects. 3D models produced by two groups, one each using the E-Scan and NextEngine, were of such good quality that they were printed in the 3D printer. The completed solid models of 6"x6" approximate size took an average of 15 hours each. Figure 4 shows one model created with NextEngine and RapidWorks with a back plate attached to it after the NURBS surface model was transferred to SolidWorks.

Figure 4. Prototype created in the 3D Printer

Course Outcomes and Students' Perception

The primary goal of this course is to prepare students for the upper level courses by exposing them to realistic problem solving methods adopted by professional engineers as well as motivate and excite them towards the challenges and rewards of a successful engineering career. The laboratory component was added specifically to increase students' familiarity with current manufacturing and testing equipment. The addition of the 3D Scanning and reverse engineering project is a natural extension of the existing laboratory projects as it involves the application of

one of the most innovative and futuristic technology in a generation. Students were required to fill out a questionnaire designed to gauge their perception about this course and laboratory projects at the end of the semester since fall of 2006. This year the original questionnaire was expanded to include questions to get a feel for this very challenging new project. Table 1 summarizes the responses from the survey questionnaire.

Table 1. Responses from the survey questionnaire administered in fall 2008 semester.
(*Note: 11 students took the survey*)

General Questions:

Q. 1) Which was the most enjoyable part of the course?

Responses	Frequency	Percentage
Lectures	4	36
Laboratory Projects	7	64
Videos on Engineering Projects	0	0
Numerical Problem Solving	0	0

Q. 2) Did the course help you better understand what engineers do in real life?

Responses	Frequency	Percentage
Yes	3	27
No	1	9
Somewhat	7	64

Q. 3) Did the knowledge and information from this course matched your expectation of what engineers do?

Responses	Frequency	Percentage
Yes	5	45
No	1	9
Not Sure	5	45

Q. 4) Did the course help you reinforce your choice of Engineering Major?

Responses	Frequency	Percentage
Yes	6	55
No	2	18
No Effect	2	18
Missing	1	9

Q. 5) Was adequate amount of material covered in each section of this course?

Responses	Frequency	Percentage
Yes	6	55
No	5	45

Q. 6) Do you think the course helped you to get better prepared for the advanced engineering courses?

Responses	Frequency	Percentage
Yes	4	36
No	2	18
Do not know	5	45

Questions specifically designed for Laboratory Projects:

Q. 7) **Which Laboratory Project you liked most and you wished to have spent more time on it?**

Responses	Frequency	Percentage
Lego NXT robots	3	27
PC Turn CNC Machine	2	18
Wind Tunnel		
SolidWorks CAD & Rapid Prototyping	4	36
3D Scanning & Reverse Engineering	2	18

Q. 8) **Has the special computer software used in this course helped improve your logical thinking ability?**

Responses	Frequency	Percentage
Yes	8	73
No	2	18
Not sure	1	9

Q. 9) **Which software appeared to be most challenging for you to understand?**

Responses	Frequency	Percentage
WinCAM CAD/CAM/NC	2	18
Mindstorm NXT	1	9
SolidWorks		
Excel		
PSI-Plot	1	9
3D Scanning/Reverse Engineering	7	64

Q.10) **Which project you would have deleted in order to spend more time on the others?**

Responses	Frequency	Percentage
Lego NXT robots		
PC Turn CNC Machine		
Wind Tunnel	8	73
SolidWorks CAD & Rapid Prototyping	1	9
3D Scanning & Reverse Engineering	2	18

Q. 11) **Do you see the similarity of the facescan project with the 3D scanner to the workflow experienced by engineers on a typical project in everyday work environment?**

Responses	Frequency	Percentage
Yes	3	27
No	1	9
Somewhat	7	64

Q. 12) **Was the level of training sufficient in operating 3D scanners to obtain the scans and align/merge them with the software?**

Responses	Frequency	Percentage
Yes	4	36
No	7	64

Q. 13) On a scale of 1 to 5 (1 being least difficult and 5 the most), how difficult was the reverse engineering software to work with?

Responses	Frequency	Percentage
1		
2	2	18
3	5	45
4	2	18
5	1	9
Missing	1	9

Q. 14) Would you have liked to scan an object rather than your partner's face?

Responses	Frequency	Percentage
Yes	8	73
No	2	18
Missing	1	9

Q. 15) On a scale of 1 to 10 (1 being very negative and 10 being very positive), describe your overall perception of the facescan project with the 3D scanners.

Responses	Frequency	Percentage
1		
2	1	9
3		
4		
5		
6		
7	6	55
8	2	18
9		
10	2	18

Q. 16) Did the Lab Manual help you understand each projects objective and procedural steps?

Responses	Frequency	Percentage
Yes	8	73
No		
Somewhat	2	18
Missing	1	9

Q. 17) Do you like to see the Lab grade change from current 30% of overall value to a different value?

Responses	Frequency	Percentage
Raise	6	55
Lower	1	9
Keep it same	4	36

As in the previous years, most students liked the laboratory projects than any other section of the course and favored increasing the lab projects grade. However, as is apparent too much material is attempted to be covered in both lecture and laboratory projects. All students felt that the wind

tunnel project should be removed perhaps because of complex nature of aerodynamic calculations and interpretation of results so that more time is available for other projects.

Though overall perception of the 3D scanning project is decidedly positive, students also expressed dissatisfaction with the level of training available with the 3D scanning and reverse engineering software. This is particularly true for those who used NextEngine scanner and RapidWorks software. This can be attributed to the complexity of the software that requires substantial amount of on the job training. However only 3 weeks was assigned for the entire facescan project. Also, NextEngine and RapidWorks being the newest addition to the lab, the manual for this project was being developed at the time and has not yet been perfected. Students also expressed a desire to scan an object rather than their partner's face as it became quickly apparent that it is extremely hard to keep still without moving a muscle for the entire minute and half of the scanning period.

Future Plan

As the course has already been overburdened with various projects and class topics, students felt somewhat overwhelmed with the amount of work expected of them particularly outside the scheduled class time. Reducing the number of laboratory projects will provide them additional time for this project and is expected to have a positive impact on the learning outcomes. In future a prismatic machine part would be used for this project as desired by majority of the students. This will remove the additional constraint of maintaining a posture for an extended period of time. Step by step instructions for both of the reverse engineering set up will be compiled and included in the manual for the laboratory projects next time the course is taught. But the biggest obstacle in order to achieve a high level of impact on students' understanding is the non-availability of a permanent laboratory assistant as trained student assistants are neither always available or can be relied upon in providing quality help when needed.

Learning Effectiveness

Engineering problem solving requires examination of various courses of action before arriving at an acceptable solution through deductive reasoning. Most upper level engineering courses require understanding of this concept which is one of the prime criteria of selection of the laboratory projects as well as other topics covered in the "Principles of Engineering" course. In general grade received by the students in this course agree reasonably well with how they fared in this laboratory project. However the real test of learning effectiveness of this project can only be revealed when students go through their upper level courses which will be monitored. In the past, it has been noted that students grade in this introductory course is a precursor of the grades obtained in subsequent engineering courses.

Conclusion

Despite occasional problems with scheduling conflict and lack of immediate assistance available, students were extremely excited about this project. There were no complains about working extra hours outside the normal scheduled laboratory class time from the students. Sometimes they even had to work in the weekend to submit the project on time which is rather unusual. Student teams took ownership of their work and competed against one another to get the "best" job done. This

is particularly gratifying to observe as it is not normal to see significant engagement in the academic work by the students other than during the test time.

Based on the overall experience it can be concluded that the that the primary goal of the laboratory component of the "Principles of Engineering" course of providing the students with realistic and engaging learning experience with current manufacturing and testing equipment has been accomplished with the introduction of this reverse engineering project.

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