AC 2010-139: CAD INSTRUCTION TECHNIQUES FOR ADVANCED ASSEMBLY MODELING AND MECHANISMS DESIGN

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CAD Instruction Techniques for Advanced Assembly Modeling and Mechanisms Design

Abstract

The Industrial Technology CAD/CAM program at Western Washington University (WWU) provides training to technologists in a range of CAD and CAM related areas. Critical amongst these is training in how to model large assemblies with moving components that can be simulated and analyzed. This takes place within the context of an advanced CAD course, ETEC 361, that uses the Assembly Modeler and Mechanisms application within Pro/Engineer®. This paper summarizes the approach taken to do this, offers observations that have been made on how it benefits CAD/CAM majors and discusses the challenges that remain.

After providing background on the IT-CAD/CAM program and the objectives of ETEC 361, a description of instructional approaches and assignments that students are required to complete is given. These include instruction in *Top-down Modeling* techniques and in assembling mechanisms for simulation and analysis purposes. Students have a basic understanding of the difference between the top-down and the bottom-up approach from freshman CAD classes. In this advanced CAD class the use of *skeletons* is introduced as another approach that applies the top-down methodology.

Examples of open-ended individual projects where students get to select a mechanism to model and analyze are presented. In addition an overview of the strategy adopted and experiences in conducting a collaborative team project for creating a complex mechanism will be discussed. This strategy enables a realistic model of an assembly with over 100 components to be modeled, simulated and analyzed within a 10 week term.

The paper concludes with a discussion of observations made on how students benefit from the instruction, assignments and project work in this advanced area of CAD. This includes their ability to assimilate and apply both the mechanics and strategies of advanced assembly modeling and the challenges faced in collaboratively creating large assemblies.

Introduction

The Engineering Technology Department at Western Washington University runs several programs that train Technologists and Industrial Designers in the area of product development. These include ABET accredited programs in Plastics and Manufacturing Engineering Technology (ET) and CAD/CAM and Vehicle Design programs that fall under the Industrial Technology (IT) umbrella. As with all technology programs a focus on hands-on project work to supplement rigorous coursework is considered critical to a well trained technologist upon graduation. Training in CAD is considered an essential component of this. Beyond just learning how to use a CAD system, much of the project work undertaken through the programs would be difficult if not impossible to accomplish without CAD modeling to support the creation of drawings and generation of CAM data to run CNC machines to produce parts and tooling.

All students in these programs take two freshman courses in Engineering Design and Graphics. The lab sections in these courses provide around 30 hours a piece of training in the use of CAD. Until recently two CAD systems, CATIA and Pro/Engineer® were used independently in each of the courses. This two system approach had evolved over time driven in part by industry participation in projects favoring a particular CAD system. There was also a desire to provide a broad exposure to CAD technology. Students in the IT-CAD/CAM program are required to take two additional courses that cover more advanced topics in CAD. These courses are in Assembly Design and Mechanisms Modeling, and in Surface Design and Modeling. The former course uses Pro/Engineer® and the latter CATIA. Again the use of two CAD systems in this way reflects the philosophy of combining depth-of-study with breadth-of-exposure. This is particularly important for CAD/CAM technologists who are likely over their careers to need to transition between CAD applications.

The rest of this paper is devoted to describing the instructional approach taken in the advanced CAD class on assembly and mechanisms modeling using Pro/Engineer®. In particular it will focus on how homework and project assignments are used to help students utilize the modeling techniques they are introduced to during tutorial sessions.

Course Overview

Since WWU operates on the quarter system, courses are scheduled over a 10 week period. As a four credit offering, ETEC 361 meets for two 3 hour periods in the department's CAD laboratory. While the size of the lab caps enrollment at 25 students, the class size is typically between 15 and 20. This adequately meets the demand for the CAD/CAM program while providing space for students in other programs wishing to take this course as an elective.

The objectives of the course are as follows:

- To introduce the modeling and analysis of mechanisms using a CAD system.
- To provide exposure to the use of top-down assembly modeling techniques.
- To expose students to the challenges faced in team-based modeling of large CAD assembly models.
- To enhance the student's understanding and skills in parametric modeling of mechanical components.

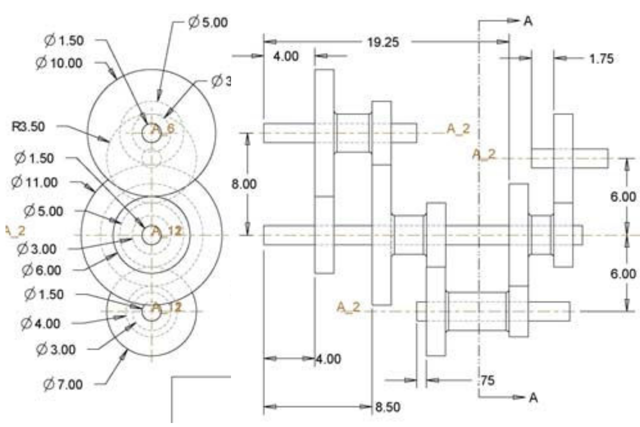
A typical 3 hour meeting of the class would contain background material on the scheduled topic, instructor led exercises and tutorial exercises that the students would complete from the training manuals that are used[1,2]. Later in the term parts of sessions are set aside to allow students to work on their projects "in-class". This helps provide an opportunity for group project teams to meet during class time and for the instructor to be able to provide guidance in problem areas that are encountered. Outside of the regularly scheduled class time students must work on a weekly homework assignment that makes them apply the material covered in the tutorials independent of instruction. There are also project deliverables that are scheduled for submission throughout the term. While the focus of the course is on assembly design and mechanisms, about 30% of the topics cover advanced part modeling techniques in Pro/Engineer®.

Understanding and Modeling Mechanisms

The freshman CAD classes introduce students to basic assembly modeling. This is the bottom-up modeling methodology where detailed components are constrained to each other using assembly relations such as *Mate*, *Align* and *Insert*. These provide static connections between the components where all 6 degrees-of-freedom are constrained (Pro/Engineer® has an option to *Allow Assumptions* that permits a rotational axis e.g. shaft in a hole to remain unconstrained). ETEC 361 expands this exposure to include connections where relative motion is permitted. These include *Pin* (1 DOF), *Slider* (1 DOF), *Cylinder* (2 DOFs), *Planar* (3 DOFs) and *Ball* (3 DOFs) connections to name a few. In addition *Gear* and *Cam* connections that relate moving components are introduced. Assignments from the training materials highlight the approach for creating connections for a variety of simple mechanisms. These help develop the student's ability to decide what connections need to be used to produce a desired motion. They also become familiar with the mechanics of using the Pro/Engineer® menus, *Assembly Dashboard* and the graphics window to model these.

Students are also exposed to the fundamentals of mechanism design that provide them with a rationale for the specifications and geometry they use in creating connections. Figures 1 and 2 illustrate two examples of homework assignments that show how these fundamentals are applied to validate the results obtained from the Pro/Engineer® models.

The first is the modeling of a gear train. The *Train Value* formula[3] shown in the figure is used to manually calculate the output RPM of the train for a given input speed. This is then compared to the measured RPM obtained from the Pro/Engineer® model with connections in place. Students are able to verify that their model has been correctly set-up and have confidence in using it with different input speeds.



$$e = \pm \frac{\prod \text{Driving Tooth Numbers}}{\prod \text{Driven Tooth Numbers}} = \pm \frac{N_1}{N_2}\frac{N_2}{N_3}\frac{N_3}{N_4}\cdots\frac{N_{n-2}}{N_{n-1}}\frac{N_{n-1}}{N_n}$$

+

$$R = \frac{\omega_2}{\omega_1} = \frac{N_1}{N_2} = \frac{d_1}{d_2} = \frac{n_2}{n_1}$$

$$\Rightarrow \quad e = -\frac{6}{10}\frac{5}{11}\frac{5}{7}\frac{4}{8}\frac{5}{7} = -0.0696$$

Figure 1. Geartrain Design Assignment

The second example is the modeling of a finite jerk cam connection. A Rise-Dwell-Fall-Dwell (RDFD) cam uses a cycloidal curve profile for the rise and fall sequences of the motion program so as to produce twice differentiable geometry to avoid acceleration spikes. The curve profile is modeled in Pro/Engineer® using the *Equation* option of the *Datum Curve* tool that allows the cycloidal geometry to be directly programmed. Validation of the cam geometry is performed using the *Measurement* tool in the Mechanisms Module that is used to generate plots of the displacement, velocity and acceleration of the follower. These are compared to the theoretical results obtained from differentiation of the curve profile.

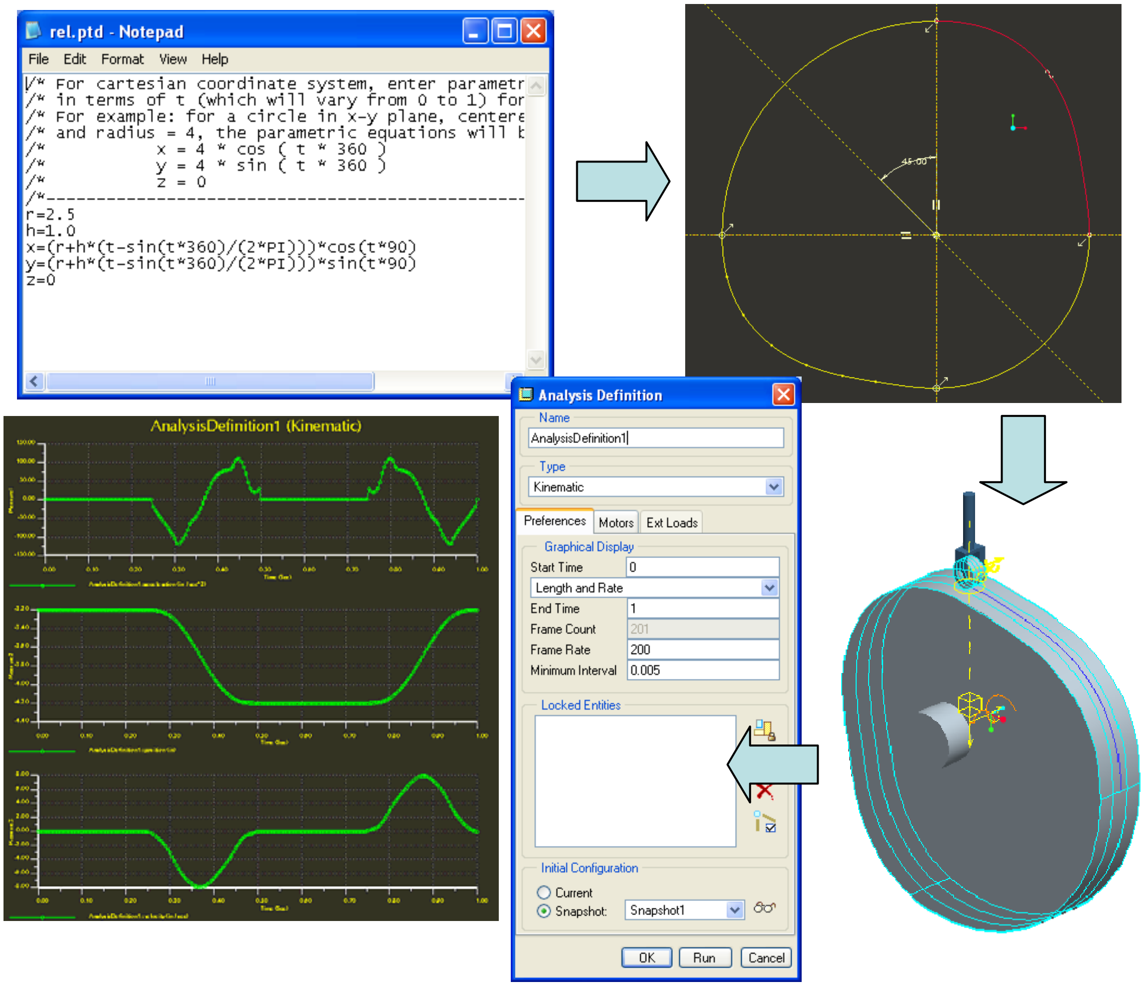


Figure 2. Cam Design Assignment

Top-down Modeling Using Skeletons

An important concept that is studied and applied in ETEC 361 is *Top-down Modeling*. Students have a basic understanding of the difference between this and the bottom-up approach from the freshman CAD classes. However, the practice of this technique has been limited to *Design-in-Place* exercises. This is when new components within an assembly are created using geometry referenced in other components. In the advanced CAD class the use of *skeletons* is introduced as another approach for applying the top-down methodology. Students are shown how a skeleton fits well with the design process that starts with a sketched concept and evolves through embodiment to the final detailed form. Different types of skeletons and their roles in modeling are introduced: *Part Skeleton, Assembly Skeleton, Motion Skeleton.* Figure 3 shows an example of a skeleton used in creating a part and assembly for a plastic tray with a cover that was created by students during an instructor led exercise.

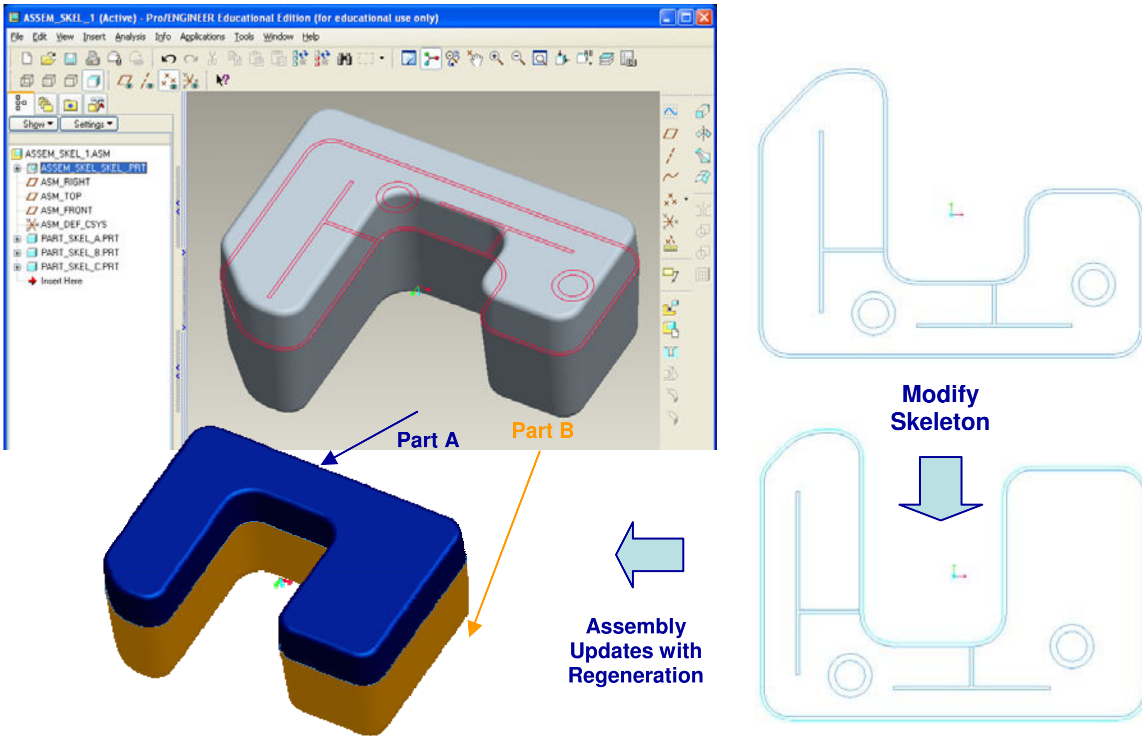
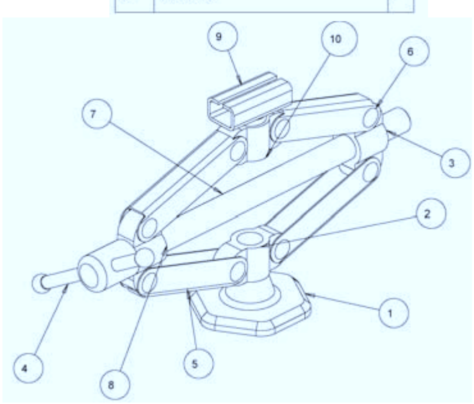


Figure 3. Part and Assembly Modeling Using a Skeleton

Index	Part Name	Qty
1	BASE	1
2	BOTTOMBLOCK	1
3	COLLARBLOCK	1
4	HANDLE	1
5	LINK	4
6	PIN	8
7	SCREW	1
8	SCREWBLOCK	1
9	TOP	1
10	TOPBLOCK	1



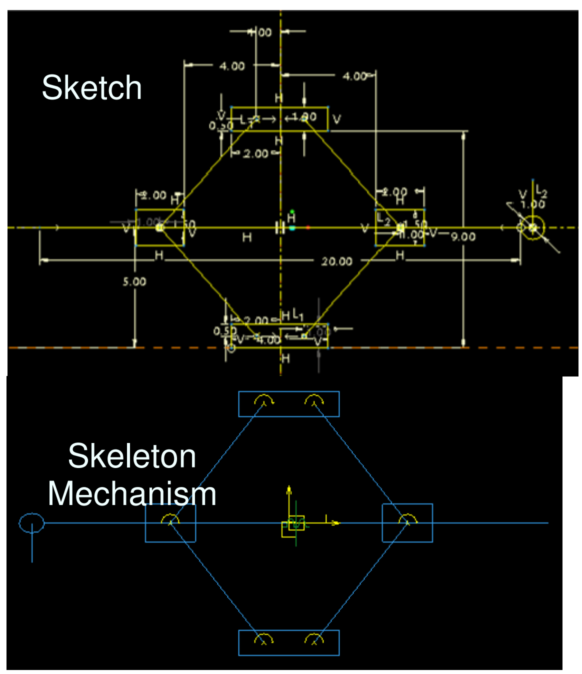


Figure 4. Motion Skeleton for a Carjack

Figure 4 shows an example of a motion skeleton used in an exercise for creating a car jack mechanism. This utilizes a series of pin joints to connect the links to the base, top, collar and threaded pieces. Pin, slider and a *rack and pinion* connection are used to connect the screw and to simulate the action of the power screw.

Individual Project Work

Each student is required to complete an individual term project that builds a mechanism starting with a motion skeleton. The project starts with a 1 page proposal after discussion with the instructor about several ideas of interest with varying complexity. Prior to modeling the skeleton in Pro/Engineer® a "paper" sketch must be drawn with joints and bodies clearly labeled. This is required to give students the opportunity to discuss their understanding of how the mechanism works with the instructor prior to investing the time in creating the model. Once completed and functioning correctly a 3D model is created using the bodies from the motion skeleton as a reference. Finally, a simple analysis must be performed using the mechanism. This might involve taking measurements of displacement, velocity and acceleration at a location of interest on one of the component's bodies or generating *trace curves* and *envelop bodies* to check for interference. Figure 5 shows examples of some of the projects completed by students. From left to right these are a linkage mechanism for a steam locomotive, a rock climbing cam and a sewing machine mechanism.

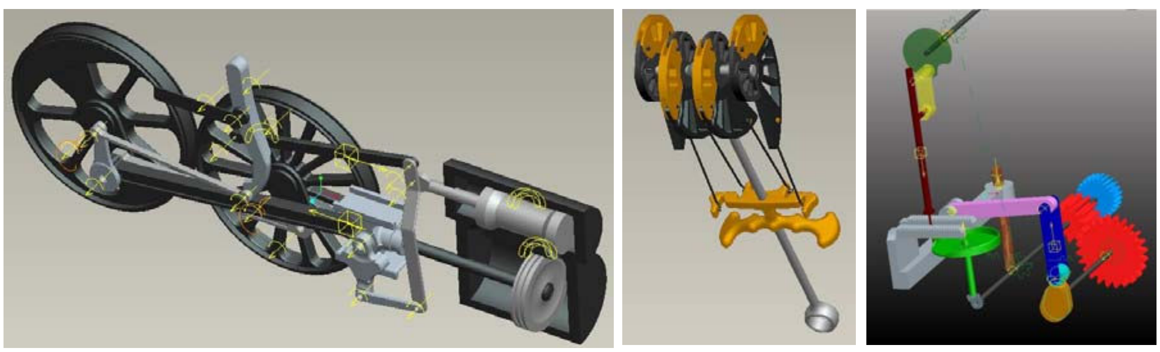


Figure 5. Examples of Mechanism Projects Completed by Students

Collaborative Modeling of a Complex Mechanism

To provide students with an experience of building a CAD model as part of a team, groups of 3 or 4 students are required to work on a project building a complex assembly with a combination of static and moving connections. This is to be accomplished using a combination of top-down and bottom-up modeling techniques. The product to be modeled is chosen by the instructor. One such example, a 1/18th scale Remote Control (RC) Racer is shown in Figure 6. These come with full suspensions for the four wheels, front and rear differentials (slip type), a gear reduction system from the motor through a drive shaft, and a steering linkage mechanism connected to a remote controlled servo unit. In total, the model has between 60 and 70 unique components (including standard components such as fasteners and bearings) and a part count of around 100.

The strategy for creating the mechanism starts with the instructor dividing its components amongst the class members to model. This is done equitably by rating the modeling complexity of each component on a scale of 1 to 5 and using this to create groupings with approximately the same rating. Some components are excluded from this (e.g. wheel rim and tire) and are to be modeled independently by each group. The class then takes a fully assembled RC Racer and disassembles it into its components. Each student is given the components they are to model. This process helps develop an understanding of how the mechanism works. Assembly instructions and the parts list that come with the racer are also provided to help in this regard. Each student is required to complete modeling of their components by the middle of the term. To do this they take rough measurements from their components and identify key dimensions to be used in parametrizing the model they build. This is essential to allow fine-tuning of component sizes by the groups as they add components to sub-assemblies. Students are encouraged to meet with their classmates who are modeling components that have connections with the components they are modeling to ensure proper fits. In addition to the models, proper documentation (drawings) must be created for each component that clearly show dimensions that can be varied.

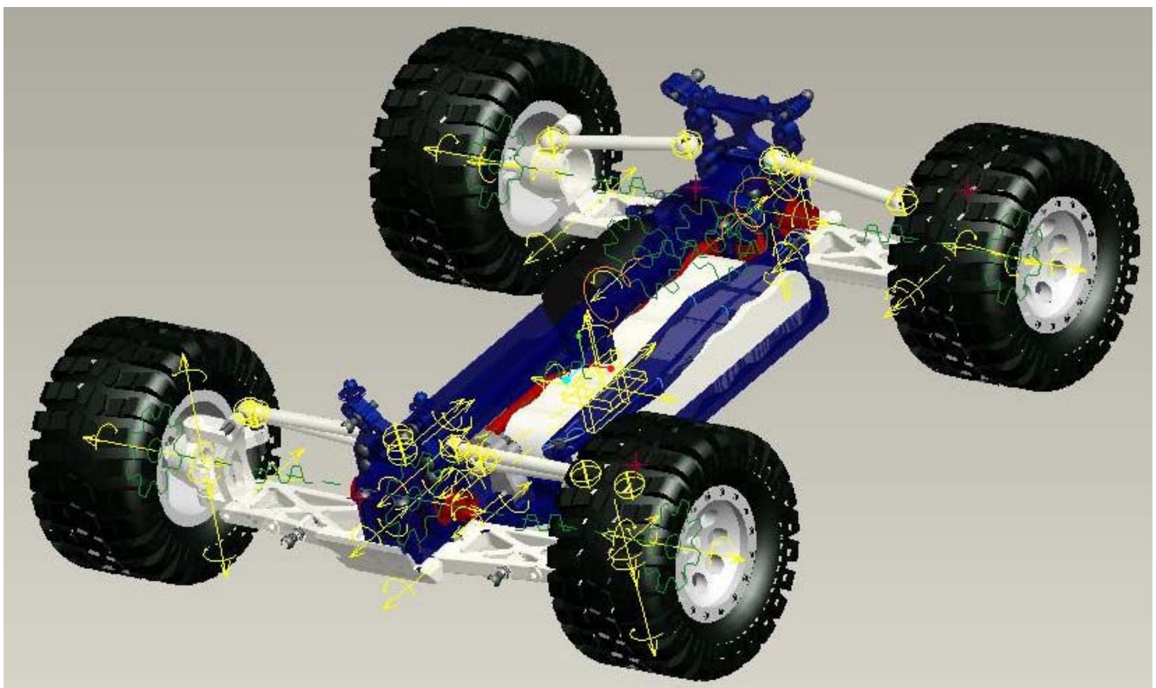


Figure 6. Example of Model Created in Team Project (1/18th Scale RC Racer)

While components are being modeled by the class as a whole, each group creates on paper an assembly structure for the RC racer model. This structure is designed in a manner that provides each student in the group with an opportunity to create a mechanism for the racer (e.g. suspension, drive train, steering system). These are modeled as sub-assemblies that integrate back into the main assembly. Using this structure an "empty" assembly model is created in Pro/Engineer® using *placed* components. This is the term used in Pro/Engineer® for including a component in an assembly structure when connections cannot be established due to details that have yet to be modeled. Creating a structure in this way is part of the top-down strategy for modeling. As the individual parts being modeled by the class become available they are used by the groups to populate the empty sub-assemblies and to turn placed components into ones that are fully constrained. This stage follows the bottom-up modeling strategy.

Observations

The following are some key observations that have been made through several offerings of this course.

- A CAD Approach to Studying Mechanisms appears well suited to training CAD/CAM technologists: The goal of the IT-CAD/CAM program is to train students to be proficient in the application of CAD/CAM technology. This is in contrast to a ME or MET (Mechanical Engineer/Technologist) where design is a critical component. In these programs courses in machine design and/or mechanisms provide focused coverage of the theory and applications. Software tools are being used in these courses that assist in the design process. These tools focus more on the synthesis and analysis of machine components and mechanisms as opposed to the detailed modeling using a CAD system. Ideally a curriculum that would allow both is desirable but difficult to achieve due to resource and time constraints. The performance of the students in this course as demonstrated by the realism captured in the project examples given show that they have been able to meet the primary goal of enhancing their modeling skills while at the same time broadening their exposure to the capabilities of software tools in studying the behavior of a mechanical system. In addition to mass property and Bill-of-Material analyses (studied in introductory courses) they are now able to model assemblies where motion can be simulated, interferences checked and kinematic measurements taken.
- The Challenge of Interpreting an Analysis: While kinematic analysis capabilities integrated into a CAD system can greatly enhance the study of a design, they can also lead to poor design decisions if used incorrectly without proper validation. The homework exercises as shown in Figures 1 and 2 are designed to show students how to validate the results obtained from an analysis using simple calculations based on theory. However, these become difficult to perform for complex mechanisms such as those shown in Figures 5 and 6. Students need to be made aware of the limitations of software solutions, the potential for mistakes in setting up the model and the need to validate results using intuition, experience and where possible, first principles.
- Importance of a Realistic, Large Assembly Modeling Experience: Creating large realistic assembly models is difficult with the time limitations of a ten week term. However, since these are the types of models often encountered in practice it is important to provide this type of experience. The approach taken of distributing the modeling activities amongst class members to create the large number of component models needed for a complex assembly seems to work well. It reduces the amount of modeling at the part design level and focuses effort on the assembly and mechanism modeling steps where the course objectives lie. Greater realism is also realized as students have more time to spend on modeling a small set of components. One problem that can arise is when students fail to complete their assigned components by the deadline. This delays the entire class. Difficulties can also arise if models are not properly parametrized to allow fine tuning of dimensions to make components fit in

the assembly. Students are encouraged to meet and discuss the interfaces of their components with their classmates and the instructor to help create "smart" models.

- The Challenge of Collaboration: Large assembly models increase the problem of data management and version control. This is particularly challenging when the modeling activity is performed collaboratively by a team. As with the above point, it is felt that this is an important experience to expose technologists to modeling in the real world. Students are instructed to create a modeling plan on paper that includes an assembly structure for the model. This is then implemented in Pro/Engineer® using the top-down modeling philosophy to create an "empty" assembly structure. It has been observed that an assembly structure that hierarchically combines components/sub-assemblies into more and more complex mechanisms provides the greatest opportunities for simultaneous modeling of the assembly by team members. For example, with the RC racer a structure that separates the powertrain from the front and rear suspensions allows these mechanisms to be modeled independently and then combined at a higher level in the structure using dog-bone links between the differentials and the wheel stub-axles. Sub-assemblies are saved as separate files and can be opened independent of the top-level assembly. This supports simultaneous modeling.

  One problem observed is when a component is used in two different sub-assemblies with slightly different dimensions. Changing the controlling parameter in one will cause the component to be incorrectly sized in the other. Students are encouraged to use the *family table* feature in Pro/Engineer® to get around this problem. This allows the designer to select the appropriate instance of the component from a set of variants based on changes to the parameter in question. Another common problem occurs when a connection created in one sub-assembly references geometry in another sub-assembly. This prevents the sub-assembly in question from being opened as a separate file (a missing reference is stored in the assembly file). Students are instructed to create the connection at the next highest level in the assembly structure that both sub-assemblies fall under to avoid this problem.
- Data Management Students are given a group folder on the file system in which to create their team project model. Sub-folders can be used to organize the model on the file system if necessary in conjunction with specifying default search paths in Pro/Engineer's *search.pro* set up file. A Product Data Management (PDM) system such as SMARTEAM could be helpful in this regard. However, its use involves a large overhead in cost for set up, operating and maintaining the system in addition to the curriculum time required to train students in its use. This problem translates into industry where many small/medium sized companies that employ technologists still rely on the "lower tech" approach of managing CAD data directly through the file system rather than with a PDM portal.
- Mechanics and Methodology in Assembly Modeling: Students in ETEC 361 learn the mechanics of using Pro/Engineer® (knowledge of the tools that are available and interaction with the GUI) through following structured training exercises during the tutorial sessions. The project work and to a lesser extent the homework challenges them to think strategically about how to create a model that is "smart" (i.e. captures design intent with the ability to generate variants and modify kinematic properties), manageable/maintainable and that can be used for collaboration in a team setting. While a wide variety of training materials are available for teaching mechanics there is little comprehensive treatment of the methodologies behind the parametric modeling of large assemblies including those with kinematics. It can be argued that this is the more important aspect of the learning experience since while mechanics change with different CAD systems and version enhancements, methodologies are

transferable and evolve more slowly over time. There is a need for better course material that systematically introduces these methodologies.

Conclusions

This paper reviews a course designed to teach advanced assembly modeling and the design of mechanisms to Engineering Technologists using Pro/Engineer®. Its objectives are to deepen the CAD modeling skills of CAD/CAM technologists and to expose them to new technologies that are being embedded in CAD applications in particular kinematics modeling. The strategy for teaching this course includes a combination of in-class tutorials, homework assignments and project work as described in this paper. Students are challenged in their projects to develop realistic models of mechanisms and to work collaboratively as a team so as to obtain an experience close to what will be encountered in the real world. Observations show that students are able to significantly enhance their skills in creating realistic and complex CAD models. Challenges remain in creating an environment that supports collaborative modeling, efficient CAD data management and in creating teaching materials that focus more on the methodologies and strategies of modeling versus the mechanics of using the CAD system.

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