

2006-541: VIRTUAL PROTOTYPING: A BRIDGE BETWEEN DESIGN AND MANUFACTURING

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Virtual Prototyping: A Bridge between Design and Manufacturing

Abstract

This paper intends to study integration of design curriculum and manufacturing curriculum via virtual prototyping. Design and manufacturing are two important subject areas in most engineering schools. Various courses are offered in these two areas. However under the current curriculum setting, the design program and manufacturing program have been developed discretely without regard to the potential benefits provided by the integration of both of them due to lack of a curricular bridge to properly link them together.

Virtual prototyping, which is also called dynamic motion simulation, is one possible solution to this problem. Virtual prototyping usually is delivered in a computational multibody dynamics (CMD) course. The CMD course is designed to build basic motion and force analysis skills of a student to inform his/her design and make the design ready for manufacturing. Introducing standalone computational multibody dynamics course is the first alternative to tie design and manufacturing together via virtual prototyping.

Virtual prototyping can also be included as a section of a computer-aided design /computer-aided manufacturing (CAD/CAM) course to link design and manufacturing. A new course entitled Applied Multibody Dynamics was initiated in the mechanical engineering program at South Dakota State University. This new course has addressed the need for engineering design linked to manufacturing. To make the course substantially fulfill its role of a bridge between the design curriculum and manufacturing curriculum, the course outcomes have been tied to the students' senior design projects. Student surveys and course assessments indicate that the course plan and design provides a promising solution to the need for integration between design curriculum and manufacturing curriculum.

Introduction

Design curriculum and manufacturing curriculum are two key subject areas in many engineering programs. Specific requirements in curricula may vary, but they encounter similar issues and challenges as far as design concept through final manufacturing production is concerned. The engineering design program and manufacturing program at South Dakota State University (SDSU) face a similar challenge.

The design curriculum for the Mechanical Engineering (ME) Department at SDSU consists of several required courses and technical elective courses as shown in Table 1. ME 240 Introduction to Mechanical Design, ME 321 Fundamentals of Machine Design, ME 418 Design of Thermal System, ME 421 Design of Machine Elements, ME 478 and ME 479 Mechanical System Design I and II are required courses for all students majoring in ME program. Another eleven technical elective course such as ME 412 Internal Combustion Engine, ME 417 Computer Aided Engineering, ME 438 Machine Design Studies & Lab, and ME 440 Computer Aided Design are offered for students having various design emphases.

Table 1: Mechanical Engineering courses related to design at SDSU

Required ME Design Courses	Samples of ME Technical Electives
ME 240 Introduction to Mechanical Design	ME 412 Internal Combustion Engines
ME 321 Fundamentals of Machine Design	ME 417 Computer Aided Engineering
ME 418 Design of Thermal Systems	ME 438 Machine Design Studies & Lab
ME 421 Design of Machine Elements	ME 440 Computer Aided Design
ME 478/479 Mechanical System Design I & II	ME 440 Analytical Thermodynamics

These courses form a solid foundation with various tiers and layers of design objectives in a traditional design curriculum structure. Though various design theories and methods are covered in these courses, these design theories and methods are introduced within design boundary and without substantial considerations of manufacturability due to lack of proper techniques.

On the other hand, manufacturing curriculum of Department of Engineering Technology and Management at SDSU also offers a wide range of manufacturing courses for students majoring in Manufacturing technology. GE 225 Survey of Machine Tool Application, MNET 231 Manufacturing Process I and Lab, MNET 334 CAM/CNC, MNET 436 Production Tooling Methods and Measurements, and MNET 320 CAD are a few course examples. These courses focus on manufacturing technologies and related processing without consideration from the engineering design point of view.

Several drawbacks exist in the current settings of these two curricula. From the course list above, it is clear there are some redundancies between the courses offered by these two programs. The CAD courses are a good example. In addition, the current curriculum does not adequately meet the needs of design for manufacturing in industries. As a matter of fact, design for manufacturing is not addressed in either program expected outcomes at this time. As a result, these programs may produce design engineers who create designs with poor manufacturability and manufacturing engineers who are weak in understanding of an overall methodology of design. The question then becomes, are there any possibilities to overcome weaknesses in the current curriculum setting? The answer is – yes.

Design for Manufacturing in the Engineering Curriculum

There are numbers of ways to address this problem. Development of a complete new course *Design for Manufacturing*^{9, 16} (DFM) is one possible avenue. In this method, the new course is a result of integration of contents of several existing courses. For example in Jerz & Fischer⁹, topics of engineering graphics, principle of design, manufacturing processes and integration technologies were combined in their new DFM course.

*Introductory Manufacturing Design*⁵ is another way to transform from a more traditional CAD course to an applied design course. Through this approach, parametric solid modeling (PSM), design for manufacturability (DFM) and student team projects have been combined to achieve the goal of design concept through manufacturing production.

Integration of design and manufacturing via the senior design project is another possible alternative¹⁵. Through a one year long senior design project, students would apply design theories to their project and eventually produce the system based on their design. In all approaches mentioned above, design and manufacturing are treated equally important.

Integration of virtual prototyping techniques into design and manufacturing curricula may provide another possible solution to these problems⁶. However, the difference here is design plays a leading role and manufacturing plays the supporting role. Virtual prototyping provides the technology to establish the bridge between design and manufacturing.

Virtual Prototyping (VP)

Virtual Prototyping, or motion simulation of a mechanical dynamic system, is an integration of multibody dynamics, computer science and numerical mathematics^{1,19} as shown in Figure 1. Within the three triads, multibody dynamics plays a key role for providing principles and methods for formation of equations of motion and constraint equations for mechanical dynamic systems. Numerical mathematics offers numerical strategies for integration of equation of motion, solutions of linear equations and solution of algebraic differential equations. Computer science offers techniques and tools for numerical computation, network communication, and computer codes writing.

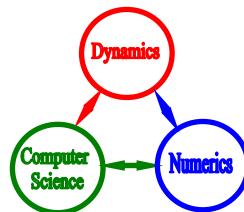


Figure 1: VP - an integration between dynamics, computer science and numerics

In practice, various physical and mechanical systems can be modeled as multibody dynamic systems. Examples of such dynamic systems include, but are not limited to: spacecraft, robotic systems, mechanisms in machinery, automotive applications, land vehicles, underwater vehicles, ships, aircraft, the human body, molecular chains in biotechnology fields and even quantum dynamics system at nano scale. Dynamical analysis determining the behavior of such devices and structures plays a key role in the design, prototype and operation of these devices and structures.

In the recent past, computational multibody dynamics was more a research topic rather than a well-established subject in mandatory college courses. Though many distinguished researchers in the field published textbooks to introduce their methods^{10, 17, 7, 8, 1, 20, 19}, few universities have offered courses in modern contexts of computational multibody dynamics. Setting up a bridge

between design and manufacturing curricula by utilization of computational multibody dynamics and related virtual prototyping software is a prospective but challenging task¹⁸.

Bridge Design and Manufacturing via VP

Conducting design in an integrated CAD/CAE/CAM environment is one possible solution to the task mentioned above^{12, 14}. VP plays a key role to bridge design and manufacturing as shown in Figure 2. For example, a suspension system can be designed in the CAD environment. Design data obtained in CAD, such as geometry and inertia properties, can be directly used in VP environment to conduct motion simulation and obtain forces and motion parameters. These forces and motion parameters may be fed back to the CAD environment to evaluate the design, conduct sensitivity analysis of the design variables and determine an optimal design. In this way, VP may not only offer motion analysis of the mechanism and check the design under the motion,

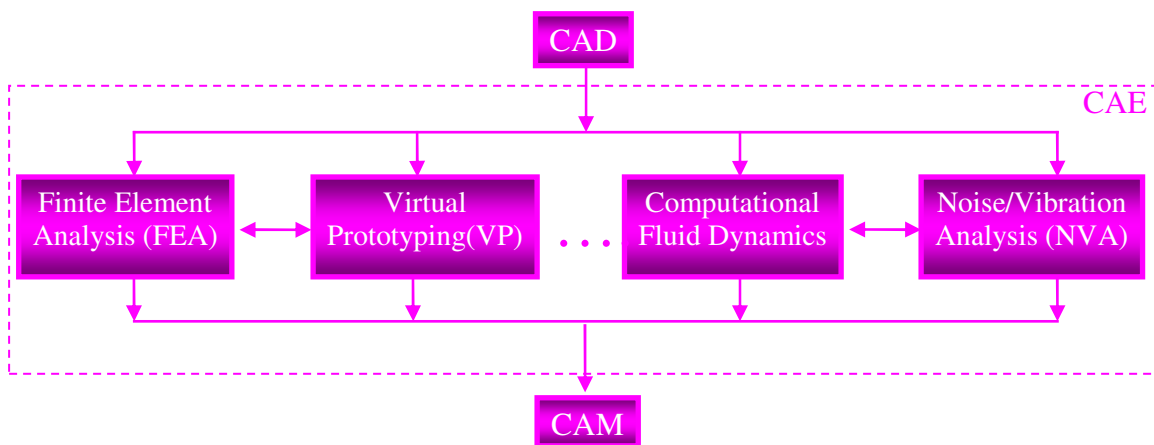


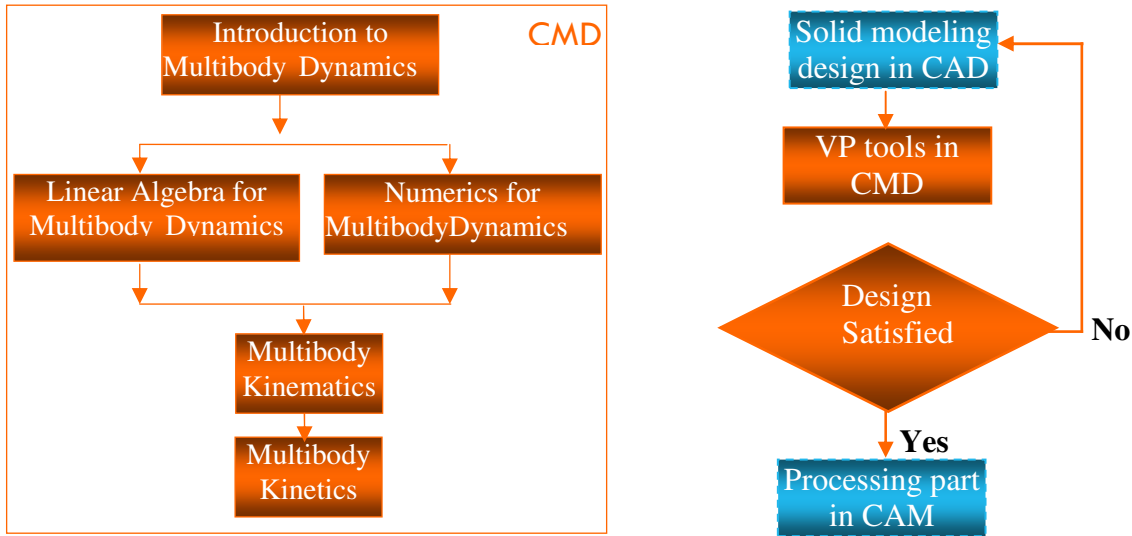
Figure 2: VP bridging design & manufacturing

but also greatly reduce the cost and production cycle time. Further data obtained from VP and CAD can be applied to finite element analysis and noise/vibration analysis. All of these prototyping and analyses are conducted on computer systems before construction of a real physical prototype. Only after all of them are verified and satisfied, should a physical suspension system then be manufactured in a CAM environment.

Two avenues exist to bridge design and manufacturing via VP curriculum development. The first alternative would be an independent course in Computational Multibody Dynamics (CMD) or Applied Multibody Dynamics to fill the gap between design and manufacturing. The other integrates VP directly into a CAD/CAM course and treats VP as an independent section after discussion of assembly modeling and before geometric dimension & tolerance (GD&T) and computer numerical control (CNC) programming. The first way will provide much deeper and broader discussion of the principles of CMD and related software applications and also illustrate the link between design and manufacturing. The emphasis would be on the subject of CMD. The second way would include VP as an extensive section of an existing CAD/CAM course. It still focuses on CAD/CAM but uses VP as extended application of CAD/CAM function module.

In the approach to CMD, multibody kinematics and kinetics, various dynamics analysis methods, and applications of linear algebra and numerical analysis to multibody systems may be

introduced. Commercial software such as MSC.ADAMS or Autolev may be used as tools for motion simulation. Design data of mechanical systems obtained from a CAD environment could be used as a case study to carry out dynamics analysis or motion simulation. Kinematical and kinetic simulation of the case in a VP environment would provide motion envelop and dead lock location check, and will further verify design. After the design is verified through VP, parts in the designed system will be processed in a CAM environment. So, another course such as CAD/CAM may collaborate or be offered alongside with the CMD course to achieve this. Figure 3 (a) represents preliminary contents covered in a CMD approach and Figure 3 (b) shows a simple thought flow between CMD and CAD/CAM courses.



(a) Preliminary contents of CMD (b) Relation between CMD & CAD/CAM

Figure 3: Approach of CMD (CAD/CAM course in blue & CMD in orange)

In the second approach, VP will be included as an extensive section of an existing CAD/CAM course after assembly modeling and before GD&T and CNC programming. Commercial software such as Pro-Engineer[®] and its Mechanism/Dynamics module may be utilized as VP tools to carry out motion simulation and verify the CAD design. The forces and motion parameters obtained in virtual prototyping may be fed back to CAD environment to conduct a sensitivity analysis of design variables and to determine an optimal design before construction of a real physical prototype. After VP verifies the CAD design, CNC codes will be post processed from the CAD model. Figure 4 represents a possible curriculum work flow for direct integration of virtual prototyping into an existing CAD/CAM course.

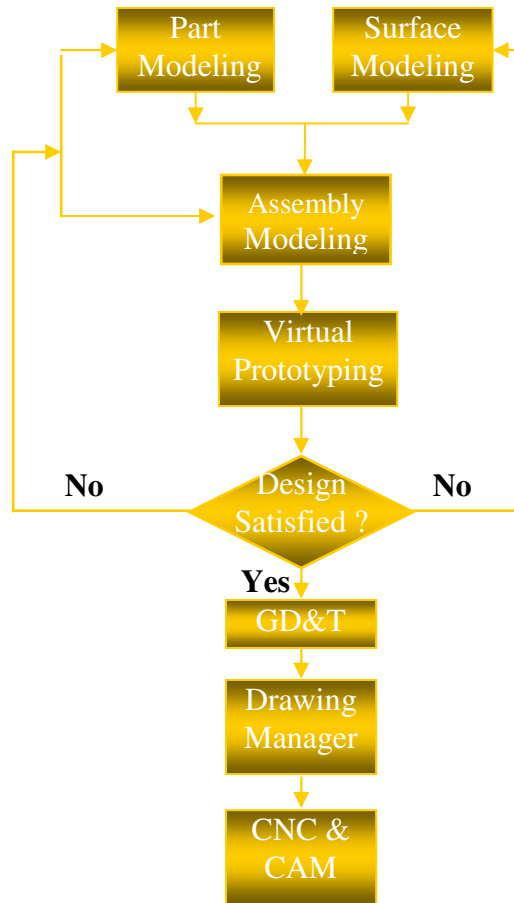


Figure 4: VP as an independent section of a CAD/CAM course

Both approaches have their strengths and weaknesses to bridge design and manufacturing via VP. If the preferred curricular focus is on verification of manufacturability of a design, then the first way may best fit program objectives. If the emphasis is on manufacturing, then the second way will be a better option. According to the design program requirements and technical background of students, CMD approach has been used to develop virtual prototyping course for students majoring in engineering design programming at SDSU.

Organization of Applied Multibody Dynamics Course in CMD approach

As a standalone and continuously evolving research discipline, computational multibody dynamics has led to the development of various methods^{14, 18}, algorithms^{2, 3} and commercial software packages¹³. They are technical resources for teaching computational multibody dynamics.

There are numbers of ways in which a multibody dynamics course can be structured and organized. But three commonly-used instructional ways are:

(1) Introduce functions, commands, user interface and user manual of commercial virtual prototyping software without having a minimal knowledge of its theoretical bases.

- (2) Introduce multibody kinematics, multibody kinetics, and various methods for equations of motion and constraint equations but without proper use of commercial virtual prototyping computer software.
- (3) Introduce both multibody dynamics theory and computer software functions in an integrated way.

The first method calls for immediate introduction to a commonly used commercial virtual prototyping software such as MSC.ADAMS and DADS (now LMS). In this way, instructional emphasis will be on the working features of the codes and user interfaces of software keeping to a minimum the knowledge of its theories base. From our extensive working experience in CAD/CAE/CAM industry, this is an efficient way to supply more adequately prepared engineers to solve the shortage of labor force and issue of learning curve time constraints. In fact, many current software users, though familiar with the graphical interface, lack the basic understanding of the theory behind the code. They have been trained by the software user manual without detailed theoretical contents and through courses or workshops organized by the software companies. But this type of training is designed for the short term and students have little potential for further development due to lack of theory background support.

Delivery of computational multibody dynamics without using any software represents another extreme. The weakness of a theory-only computational multibody dynamics course is obvious. It will not produce students who can solve the issues in a real world environment using appropriate workplace tools rather than the idealized home work problems on paper. It will not help to achieve the goal of bridging design and manufacturing together either. Thus, introducing both theory and use of software simultaneously has been the preferred method to structure and organize CMD at SDSU. Introduction of both theory and use of software will enhance students' ability to interpret simulation results obtained by virtual prototyping. Compared with software-only teaching approach, it will extend knowledge life span of a student as a software user due to learning theory background. One the other hand, the theory and software combined approach keeps students more interested in both subject and learning than a theory-only approach since students are usually attracted by the use of simulation tools. In the approaches mentioned above, each way has its strengths and weaknesses. The following table shows a brief comparison.

Table 2: Brief comparison of three different ways to organize CMD

Emphasis of course contents	Level of course	Time constraint	% of use of software	Difficulty of course
Software-orientated	Workshop to train software user	High	High	Low
Theory-orientated	Ph.D. level graduate course	Low	Low	High
Theory/ software combined	College level course for undergraduates & 1 st year graduates	Middle	Middle	Middle

Though theory and software combined approach has more benefits, determination of percentage ratio of theory vs. use of software is a challenging task for course design. Selection of software and textbook is another important issue for course organization. In dual number course ME 592-03/492-03 Applied Multibody Dynamics, virtual prototyping software Autolev¹⁴ and

accompanying textbook¹¹ have been used to meet the need to provide an appropriate ratio of theory and software usage.

Autolev is a symbolic computational multibody dynamics program. Like other popular virtual prototyping software, Autolev is very versatile and powerful, but Autolev can be used effectively only by individuals with a good theoretical background in multibody dynamics. Unlike other popular 'black box' types of virtual prototyping software such as MSC.ADAMS that the user can not see theory behind the software, Autolev commands and multibody dynamics theory are transparent to the user through the command line prompt user interface. Autolev can be treated as 'white box' type of software package, in which the user can see theory equivalent commands as they are executed line by line. Also, the symbolic feature of Autolev allows students to take a look at motion and constraint equations produced by the software codes. Thus Autolev is a suitable candidate to be used to teach CMD in the theory and use of software combined approach. However, Autolev is developed from Kane's methods, which are often difficult for undergraduates with only a basic dynamics background. Thus the instructor should provide more time to pave the path between basic dynamics and Kane's methods.

Preparing & Teaching ME 592-03/492-03 Applied Multibody Dynamics

ME 492-03/592-03 Applied Multibody Dynamics is a technical elective three credit course for seniors and the first year graduate students in Engineering. Students usually have little or no background in computational multibody dynamics nor with experience of virtual prototyping software. The course has been prepared as such:

1. Brief course description
Analytical and numerical analysis of dynamic behavior of multibody mechanical systems. Emphasis on understanding aspects of modeling and analysis process associated with dynamic systems. Review of traditional dynamic analysis methods (including Kane's method). Comparison of the different formulations and their applicability of computer simulation. Treatment of constraints, extraction of data from equations of motion, and computational issues. Preliminary of CAD/CAE/CAM integration and use of Autolev motion simulation software
2. Prerequisites
Student should have a background in physics, numerical analysis and machinery dynamics or dynamics. Basic computer knowledge and programming skills are also required.
3. Textbook & reference books
 - (1) Thomas R. Kane/David A. Levinson, Dynamics Online: Theory and Implementation with Autolev, Online Dynamics, Inc., 2000
 - (2) Ahmed A. Shabana, Computational Dynamics, 2nd edition, Wiley, 2001
 - (3) Jerry H. Ginsberg, Advanced Engineering Dynamics, 2nd edition, Cambridge University Press, 1998
4. Topics
 - (1) Introduction to multibody dynamics & Autolev
 - (2) Vector differentiation and matrix operations
 - (3) Intermediate reference frames and angular velocity
 - (4) Degree of freedom and generalized coordinates

- (5) Velocity, acceleration, angular velocity and angular accelerations of a rigid body
- (6) Generalized speeds, partial velocity and partial angular velocity
- (7) Rigid body kinematical derivative formulation
- (8) Coordinates transformations and transformation matrix
- (9) Inertia properties and generalized inertia forces.
- (10) Newton-Euler equations and Lagrange's equations
- (11) Kane's equations
- (12) Holonomic & non-holonomic constraints in constrained multibody systems
- (13) Extraction of data from equations of motion
- (14) Reduction and Augmented approaches. State-space form and descriptor form.
- (15) Numerical issues, computer simulation and integration of CAD/CAE/CAM

5. Course grading

Reading assignments	5%
Homework, quizzes & computing assignments	25%
Course Projects	20%
Two tests (15% each)	30%
Final exam	20%

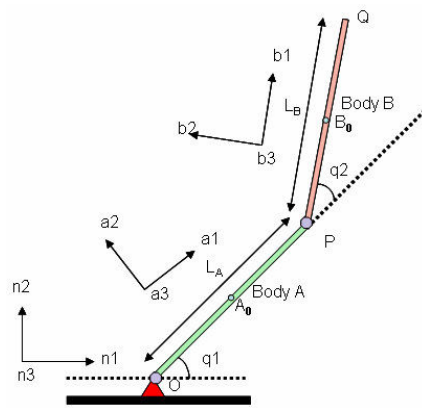
6. Course length

Forty lectures were delivered during fall semester 2005. There were three lectures each week and each lecture took fifty minutes.

Strategies of teaching through examples⁴ have been utilized to deliver the course. Various mechanical systems and dynamics models have been used as samples to combine theory and use of software together. For example, to teach general workflow and how to use Kane's equation solving real problems, a power lift with manipulator is simplified into a typical dynamic model of two rigid body manipulator as shown in Figure 5 (a) and (b). Then the model has been used as samples to discuss theory and code commands. Further general problem solving procedures of using Kane's equations and Autolev for an unconstrained system is summarized as shown in flow charts of Figure 6.



(a) A power lift in work place



(b) Simplified model of 2D manipulator

Figure 5: Extract dynamic model from real applications

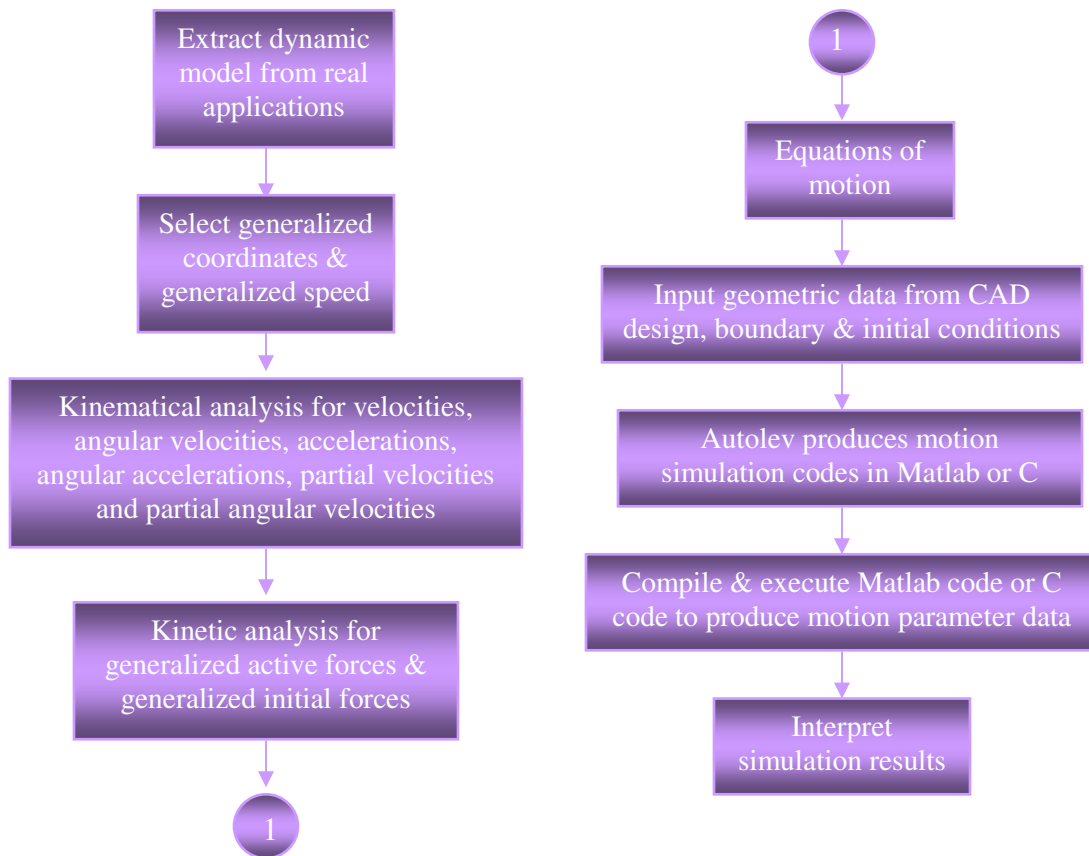


Figure 6: Work flow chart using Kane's equation & Autolev to solve a problem

Considerations to Bridge Design & Manufacturing in ME 592-03/492-03

Course projects were used as one of tools to achieve this purpose. There were two course projects. Three students formed a project team and worked together through the entire semester. The first project was assigned by the instructor and took 6% of the total project grade. The purpose of the first project was to walk students through a simple virtual prototyping procedure step by step. So they could work independently on the second project. The second project took 14% of the total project grade. The topic of the second project was selected by each project team. The topic would be senior design project, Mini-Baja project, or a real dynamic system of interest to all team members to design, model, simulate, and analyze. This project was divided into three phases. The basic requirements of each phase are listed in table 3 below. Figure 7 shows some examples of selected team projects.

Table 3: Three phases for selected team project

	Phase I	Phase II	Phase III
Requirements	1. project proposal 2. design/modeling	1. kinematical & kinetic analysis 2. dynamic analysis	1. interpret results 2. verify design for manufacturability
Presentations	1. proposal/model presentation 2. evaluation	1. derivation/code presentation 2. evaluation	1. final results presentation 2. evaluation

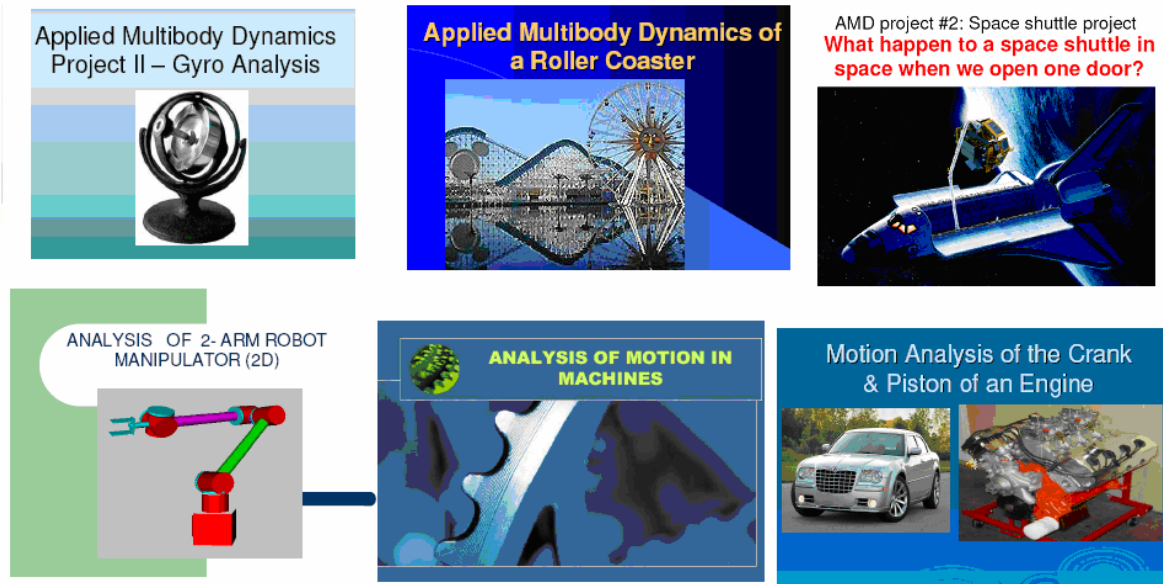


Figure 7: Selected project titles of project II in ME 592-03/492-03

Student survey & response to ME 492-03/592-03

An anonymous student survey was conducted to obtain evaluation for teaching improvement and learning outcomes. Twenty students majoring in mechanical or manufacturing engineering took part in the survey. Among them, twelve are graduates and eight senior undergraduates. Table 4 shows percentage of students strongly agreeing or agreeing with course outcomes from the survey.

Table 4: Course outcomes from student survey

	My Learning increased in this course	I made progress towards achieving course objectives	My interest in subject increased	Course helps me to think independently about subject	I involved in what I am learning
% of students	76%	75%	75%	73%	77%

Conclusion

Virtual prototyping as a tool to bridge design and manufacturing has been discussed and presented. Introducing a new CMD course between design and manufacturing curricula is one possible avenue to pave the path from design through manufacturing. Organization of the course in a way to combined theory and use of software is proper method to achieve the goal. Dual ME 592-03/492-03 offered for students majoring in design and manufacturing program in SDSU has provided the first hand experience for the future improvement and further investigation.

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