

A Case for Scaffolded Virtual Prototyping Tutorial Case-Studies in Engineering Education*

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By permitting designers to realistically, accurately and quantitatively prototype and test multiple intermediate models within virtual environment, Virtual Prototyping (VP), also known as Simulation-Based Design (SBD), has rapidly gained popularity and become a crucial part of most engineering design processes. While there is a significant demand from industry for students trained in this methodology, currently there is not much room in engineering curricula to permit widespread adoption in the lecture-based classroom. It is possible to develop a rationale and its various stages for a series of web-based and self-paced scaffolded VP tutorial case-studies targeted at students on a course in machine and mechanism design. These undergraduate seniors are permitted to: (1) interactively explore the process of creating engineering analysis models in an integrated VP environment; (2) develop skills for interactive SBD of models; and (3) develop their engineering judgment by interactive exploration of a spectrum of examples. The outcome of a phased introduction of these exercises and our experience based on a number of successful courses offering are also discussed.

Keywords: Mechanisms and machines; engineering design; simulation-based-design refinement; web-based implementation; interactive exploration; self-paced scaffolded tutorials

INTRODUCTION

LARGE NUMBERS OF CAD (Computer Aided Design) software and technology tools are currently commercially available to support simulation-based design refinement of mechanical systems. Many of these tools not only allow a user to geometrically model mechanical devices in a 3D virtual environment, but also permit the simulation and testing of product functionality virtually in a process known as Virtual Prototyping (VP). Such VP approaches derive their many advantages primarily by eliminating the need for intermediate physical prototypes at the design refinement stage. Fig. 1 compares the conventional and VP approaches for an engineering design process, highlighting the fact that iterative modification of a physical design before manufacture can be expensive and time consuming. Such use of integrated design tools/environments facilitates detailed designs to be examined even at early conceptual stages—thereby helping with improved quantitative conceptualization and shortening the design cycle [1].

Two trends that have favoured the adoption and rapid proliferation of the VP approach are the:

1. availability of low-cost PC based parametric simulation and analysis tools;

2. capability of integrating multiple functionalities into a unified environment.

Today, computer simulation may be used to compute and calculate the kinematic, dynamic and FEA-based responses of a prototype completely within the computer and the result can be visualized within a 3D interactive graphical virtual environment. Further, the ubiquitous availability of low-cost personal computer processor with accelerated graphics hardware coupled with the ease of availability of the tools for such platforms has set the stage for this new phase in engineering, enabling the designer to quantitatively evaluate the performance of a proposed design completely in software. The trend of integrating different modules and packages has permitted users not only to create the geometry for the mechanical devices of interest, but also to test the product by functional simulation within the virtual environment and ultimately to iteratively refine the design based on the result of such multi-domain simulations. Increasingly, modern-day engineering school graduates are required to be proficient in their use. However, the lack of room in the traditional undergraduate engineering curriculum coupled with the lack of an audience-specific structured learning frameworks have posed barriers.

Several innovative solutions, in the form of ‘virtual labs’ that leverage the ongoing revolutions in computing and communication infrastructures, have been considered. Virtual access labs and

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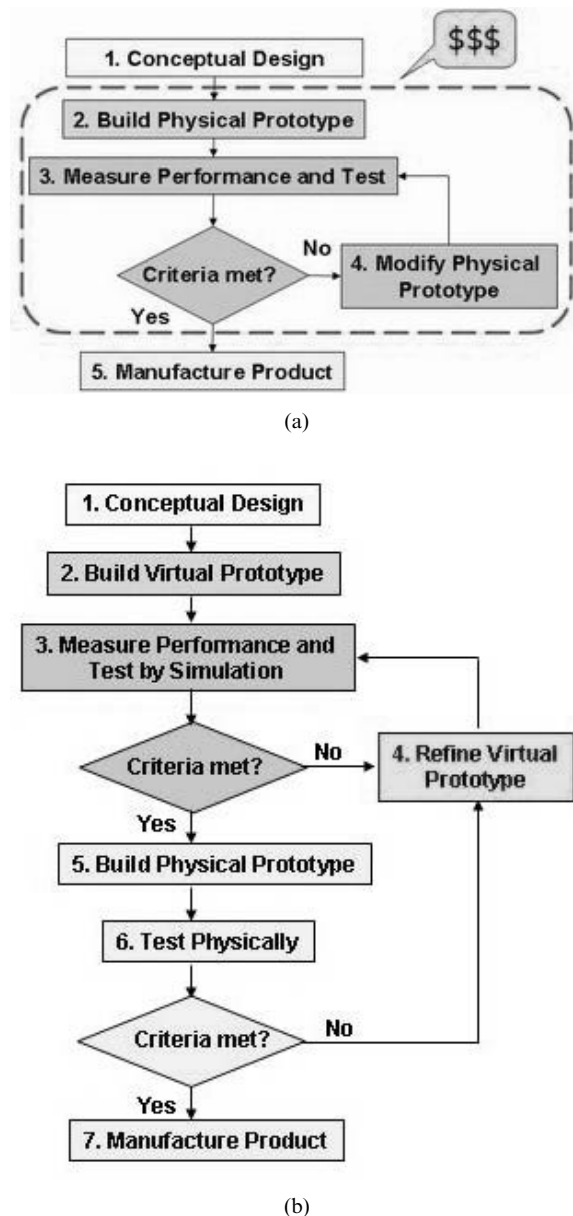


Fig 1. Comparison between (a) conventional approach and (b) VP approach in an engineering design process.

asynchronous experiments have focused on providing remote web-based access to restricted resources such as hydraulics experiments [2] or robotic arms [3, 4]. Other virtual labs take the form of supplementary interactive educational technology modules/curricula, that provide enhanced audio-visual interactivity, e.g. increased immersion within 3D VRML-based worlds [5], or Java and shockwave-based animation to illustrate non-traditional manufacturing processes [6]. Such efforts have had tremendous success in addressing a broad range of educational objectives [7]; accommodating different learning styles [4] and students from diverse educational backgrounds [8, 9]; also in serving as modular mechanisms for dissemination [8].

However, the true power of such virtual labs comes to the forefront as one begins to parametri-

cally interact, simulate and explore the design space, thus developing a more intuitive understanding of the underlying physics. From this viewpoint, the control systems literature has many examples of approaches incorporating parametric interactivity in studying plant/controller system dynamics [10–12]. We leverage a similar parametric interactivity in implementing in our tutorials.

While there are undoubtedly tremendous benefits to be derived in terms of enhanced productivity, there are also numerous issues surrounding the successful use of these new and sophisticated tools. Traditionally, many levels of ‘scaffolding’ are usually required in training of users—wherein an expert in the field helps a novice learner succeed in complex tasks that would otherwise be beyond his/her reach [13]. The two critical desired features of such a learning framework are:

1. learners receive varying levels of task- and context-dependent assistance;
2. learners draw from that experience and improve in process, skills and/or content understanding.

However, the development of a systematic mechanism for capture and subsequent transfer of experience and skills has proved to be difficult despite the availability and use of immersive and interactive multimedia software principally due to the lack of structured frameworks [14, 15].

It is to address this shortfall that we developed this series of web-based self-paced scaffolded VP tutorial case studies for a target audience of students in a senior-level machines and mechanisms course. These case studies have a natural hierarchical staging in the form of increasingly ‘problematic’ components at subsequent levels as students gain mastery at the initial levels [16, 17]. In addition, we also incorporated erroneous (but ‘intuitive’) directives at several places within the tutorials. This is intended to force students to make common but undesirable mistakes and to then benefit from the experiential learning process. In doing so, our approach is closer to Linn’s framework for scaffolded knowledge integration [18] which emphasizes the merits of such trial-and-error learning as well as the applicability of multiple equally-valid alternative approaches to problem solution. Ultimately, the principal desired outcome of these tutorials is to promote the development of cognitive inquiry within the student and accelerating the learning experience without increasing the lecture hours. At the same time the created framework also helps us address the more immediate goals of reinforcement of concepts being presented in the course by paralleling the course material in the case studies.

MOTIVATION

The effective use of many of the commercially-available, sophisticated Virtual Prototyping software tools requires ‘expert users’ who can model,

test and analyze the results for their correctness. Vendor-supplied tutorials and training, when available, tend to be targeted towards a more experienced user (typically with an industrial design background and accustomed to the use of such Computer Aided Engineering tools). Thus, such tutorials tend to assume (and rely on) a certain level of both proficiency and engineering experience from the user to enable them to gain expertise in the new tool in the shortest possible time.

In our case, it is important to tailor these tutorials towards an undergraduate student who would most likely be a novice user of this class of tools. Furthermore, as a novice user, the student would still be learning many engineering aspects and therefore has limited experience. Moreover, it is crucial that student gains a greater insight into the problem and is better equipped to make engineering judgments from the information obtained from the use of such commercial VP software. It is to promote this type of greater understanding that we are creating these tutorials, and we emphasize this at various stages in this paper.

Traditionally, many of the concepts and ideas behind mechanism theory (including the study of kinematics and dynamics of mechanisms), are delivered in a classroom-based lecture. In this setting, it tends to be difficult to demonstrate the motions of the mechanism of interest (in the absence of a physical model). Therefore, often the students are unable to easily visualize many of the kinematic and dynamic concepts such as limiting conditions, Grashof conditions or get an idea of forces and torques necessary to create a certain motion.

However, mathematical formulations of the mechanism are usually emphasized and students are required to formulate the equations governing the kinematics and dynamics of some simple mechanism and then solve these using algebraic techniques described in the standard textbooks [19–21]. The main advantage of our approach is that it permits the student to understand the fundamental theory underlying the analysis as well as get a handle on the formulation that forms the basis for the analysis of more complicated mechanisms. Thus, with a grasp of the basic concepts and formulations, students can implement the techniques algorithmically by suitably programming. Since algorithmic implementation of such analytical formulations form the basis of the virtual prototyping analysis tools, it gives the student greater insight and exposure to the underlying techniques [22–25]. However, the complexity of the analyzed mechanism imposes limitations on the analytical method. For example, the formulation of a set of equations for a simple four bar mechanism is manageable; however, if the shape of the linkage is complicated or the links number increased, the formulation becomes more complicated and time consuming. Thus, the analytical method is most often typically limited to simple

two-dimensional mechanisms and links with relatively simple geometries.

Many of these problems can be alleviated by using ‘virtual model’ and ‘virtual experimentation’ with the help of commercial tools. The main benefits of this method are that the students can analyze more complex mechanisms with detailed link geometries, obtain quick results and compare many possibilities before selecting the best mechanism by permitting the detailed visualization of virtual mechanisms, giving the student a better understanding of the motion of the mechanism, the path of a specific point and the functionality of the mechanism. The principal disadvantage is that the formulations of the kinematic and dynamic analysis of the mechanism are completely hidden from the student. The black box approach to the underlying governing equations can in many cases hinder understanding of the concepts behind many of the mechanisms.

TUTORIAL IMPLEMENTATION

Our goal is to create a linkage between the virtual prototyping approach and the traditional analytical approach so that the student can derive benefits from both—better understanding of the problem as well as greater proficiency in different methods available to solve it. The lecture coverage of the course emphasized the use of the traditional low-resolution techniques coupled with simplified analytical and computational solution methods to obtain approximate solutions while independent prototyping exploration by the student with the tutorial promoted interactive experiential learning (see Fig. 2).

We use Solid Edge V11 [26] with the Dynamic Designer plug-in [27] as the principal commercially available VP tool to simulate various mechanisms and output the performance information (e.g. part interference, motor size, cam performance, gear and linkage layout, etc.). Some of the considerations behind the selection and implementation of these two particular tools as the software of choice for this class included:

1. accessibility of the software within the university;
2. ease of learning (within a semester or less);
3. unified VP environment provided by these tools.

Such virtual models are also made available to the entire class to facilitate further exploration of many of these concepts on an individual basis by ‘Virtual Experimentation’. Every student in the class had access to the virtual prototyping software on their personal computers and on public computers in the university. With an Internet-enabled browser, each student is able to individually browse through the tutorial content while independently trying out the examples at his or her own pace. This approach also shares numerous features with Problem-Based

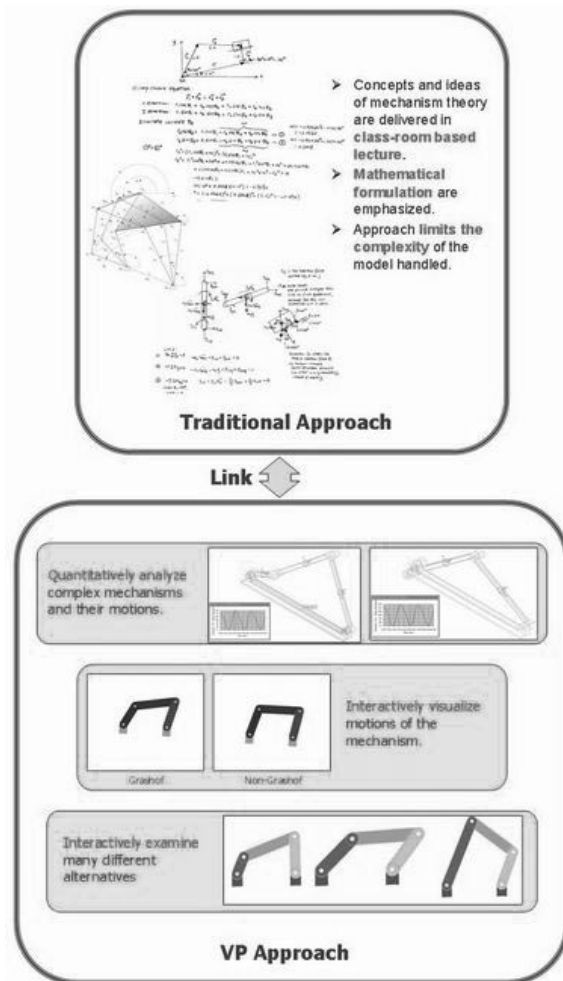


Fig. 2. Same examples are used for in-class teaching using traditional approach and online VP approach.

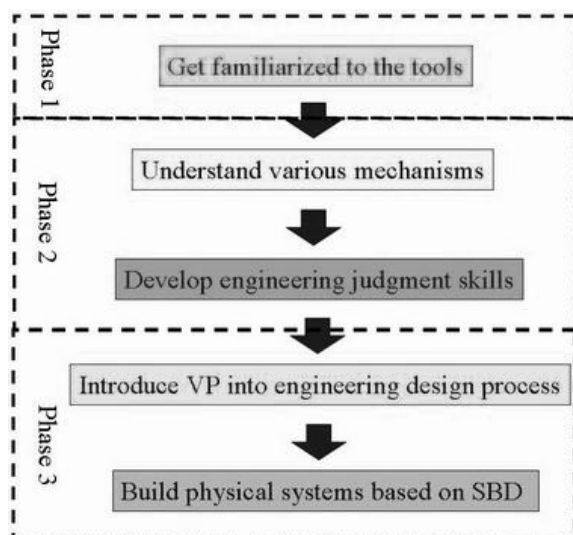


Fig. 3. Organization of the tutorial.

Learning (PBL) approaches (and their variants) [17, 28]. In particular, we seek to derive the benefit of greater levels of involvement and thereby increased comprehension inherent to these directed learning approaches.

As shown in Fig. 3, in the first phase, the student begins with a series of simple case studies that are intended to make familiar some of the basic functions in the Dynamic Designer environment within Solid Edge with the help of the examples and theory learned in the classroom. In the second phase, given some unassembled mechanism examples, students assemble the model in Solid Edge and use what they have learned in the previous steps to study the functional performance of the mechanisms. Finally, in the third phase, students used what they have learned in this tutorial to support their final design project of this course. The final project requires students to use the software to explore different options in their designed model, interactively refine the ‘virtual prototype’ of their specific designed models and come up with a final design, which meets the specifications.

PHASE-I TUTORIAL CASE-STUDIES

The goal of such case-studies is to familiarize the students with the tools using a known simple example. A representative sample of the Phase-I tutorials is shown in the simple pendulum example. The tutorial begins with a problem statement presented as:

A pendulum of length of L , as shown in Fig. 4(a), with a bob of mass m is pulled back to reach an initial angle of θ_0 from the vertical reference line and then released from rest. Determine the velocity of the mass at the lowest point of its swing.

This problem is selected to be the first example both from the viewpoint of its simplicity as well as its familiarity to the students. We demonstrate the process of modelling and the solution first by the traditional analytical approach, and then demonstrate the same process with VP approach. In the analytical approach, we discuss the following staged solution process:

1. Idealize the problem by making some assumptions, like lumped mass model at the centre of gravity (CG).
2. Draw the free body diagram of the simplified model.
3. Develop the appropriate governing equation of motions (EOM) using Newton’s Laws of Motion.
4. Solve the EOM to obtain the desired solution.

In the VP approach, the students are required to convert the simplified model into the virtual prototype shown in Fig. 4(b). The tutorial shows the students how to create the parts and how the mechanism is assembled into the required initial configuration in Solid Edge environment. The virtual model is then switched to Dynamic Designer environment in order to simulate and visualize its motion.

Fig. 5 depicts the instructions given to the students for simulating the motion and plotting

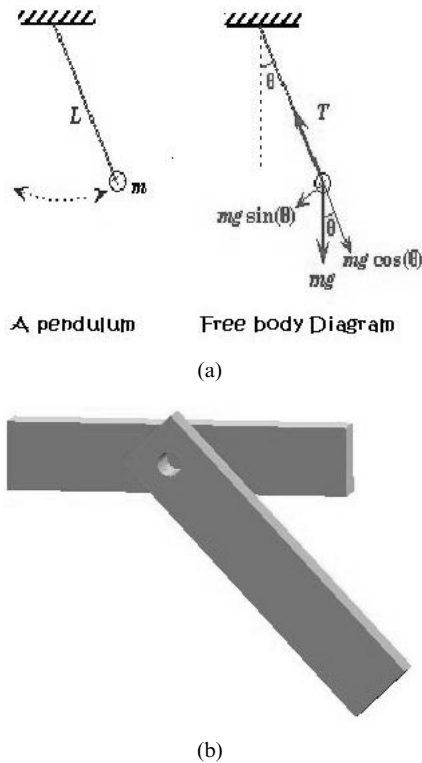


Fig. 4. Simple pendulum problem formulated by (a) traditional analytical approach and (b) VP approach.

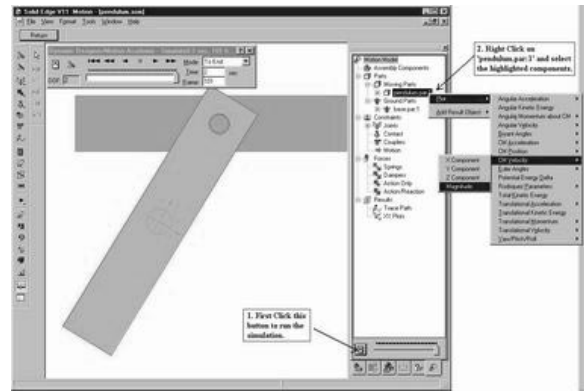
the results of this pendulum in virtual environment. The tutorial also shows the steps to analyze the graphs obtained in order to solve the problem.

However, it is important to motivate the students to exercise good engineering judgment while analyzing many of these virtual models. For example, since the simulations are done numerically, students are required to use their engineering knowledge to detect any inconsistencies, if present. In this pendulum example, the principle of conservation of energy is well understood even by these novice students. By creating a simple ‘measure’ of the total energy, issues such as the stability and step size to the numerical simulation are also explored.

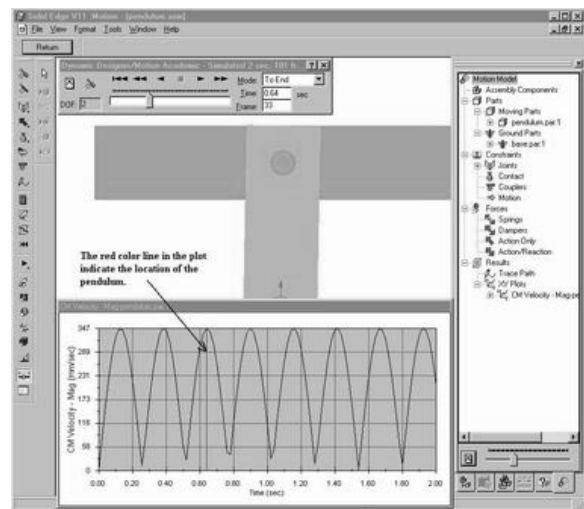
In particular, we adopted the approach of first creating scenarios that caused errors, and then working the students through the process of resolving these errors. For example, by using a link as the model for the pendulum, the effective VP model has both lumped mass at the CG and lumped inertia about the CG, which can affect the resulting motion. The tutorial guided the students to recognize this error, and work their way to overcome this problem.

PHASE-II TUTORIAL CASE-STUDIES

In the second phase, we examine more complicated examples of different planar mechanisms. For example, we study a four-bar lawn sprinkler,



(a)



(b)

Fig. 5. Instructions to (a) simulate the motion of the pendulum and plot the engineering graph, and (b) show the desired plot at an intermediate instant of time.

as shown in Fig. 6(a), with the problem statement described as the following:

Given the link lengths of a four-bar lawn sprinkler mechanism, as shown in Fig. 6(b):

- Analyze its rotatability and its limiting position.
- Given the values of the angles θ_1 and θ_2 , determine the angles θ_3 and θ_4 .
- If Joint 2 is rotating at an angular velocity of ω_2 and an angular acceleration of α_2 , determine the angular velocities and accelerations of the other joints.
- Given the mass and moment of inertia of the links, determine the actuation torque τ_4 required at joint 4 in order to drive the system at the required velocity and acceleration.

In the analytical approach, we could apply the Grashof criterion to determine the type of mechanism (crank-rocker) based solely on the link lengths [19, 20]. Using the VP approach, we reinforce the understanding of the idea by having the students visualize the same concept in the virtual environment. The limiting position analysis can also be easily demonstrated and reinforced by a combina-

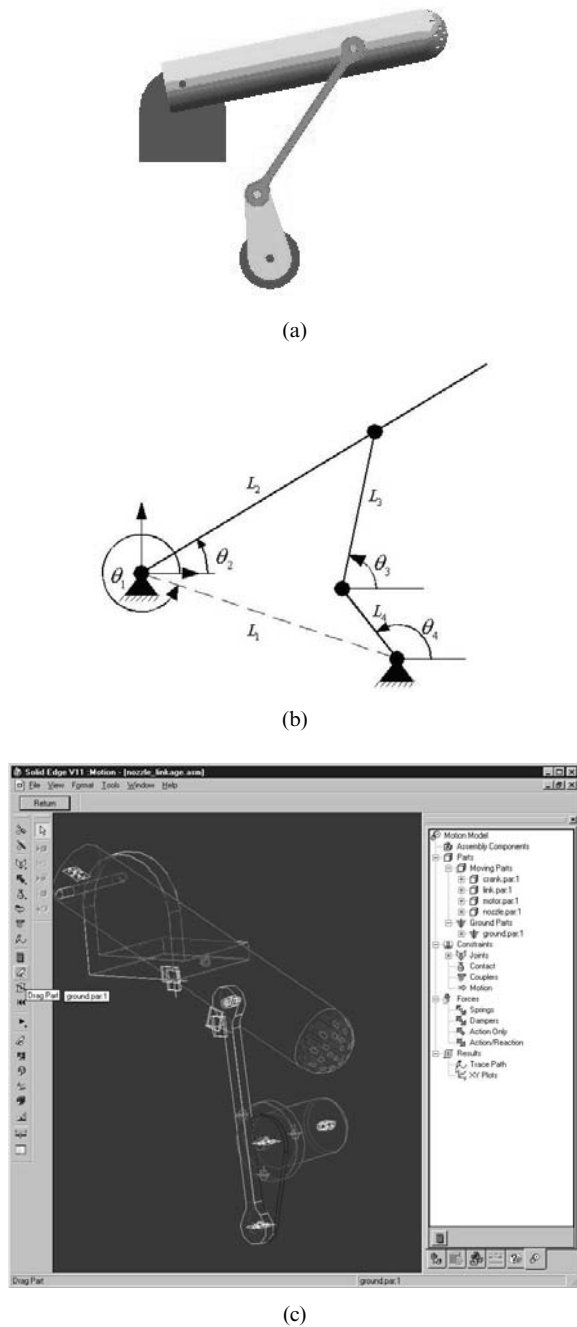


Fig. 6. (a) Four-bar lawn sprinkler, (b) its simplified skeleton model, (c) VP of the mechanism.

tion of both approaches. For a given set of parameters, the analytical approach can yield the limiting position easily by geometrical analysis [19, 20], which can then be visualized in the virtual model to improve understanding. Furthermore, by parametrically changing the link lengths, this process is then extended to help the students iteratively design the sprinkler for a desired range of operation.

Similarly, at each stage of the kinematic and dynamic analysis, the correspondence between the analytical approach [19–21] and the VP approaches are also emphasized at the same place. Finally, we also let the students explore the trade-off between

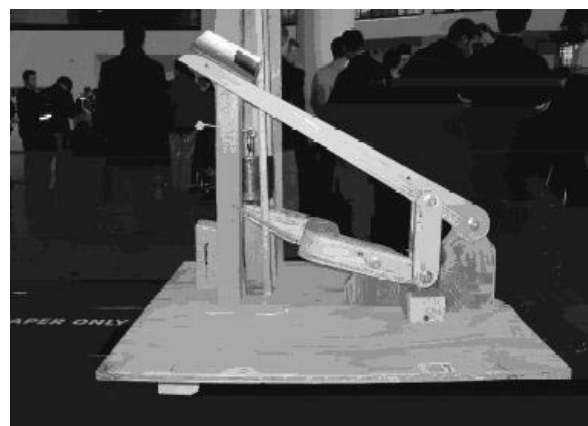
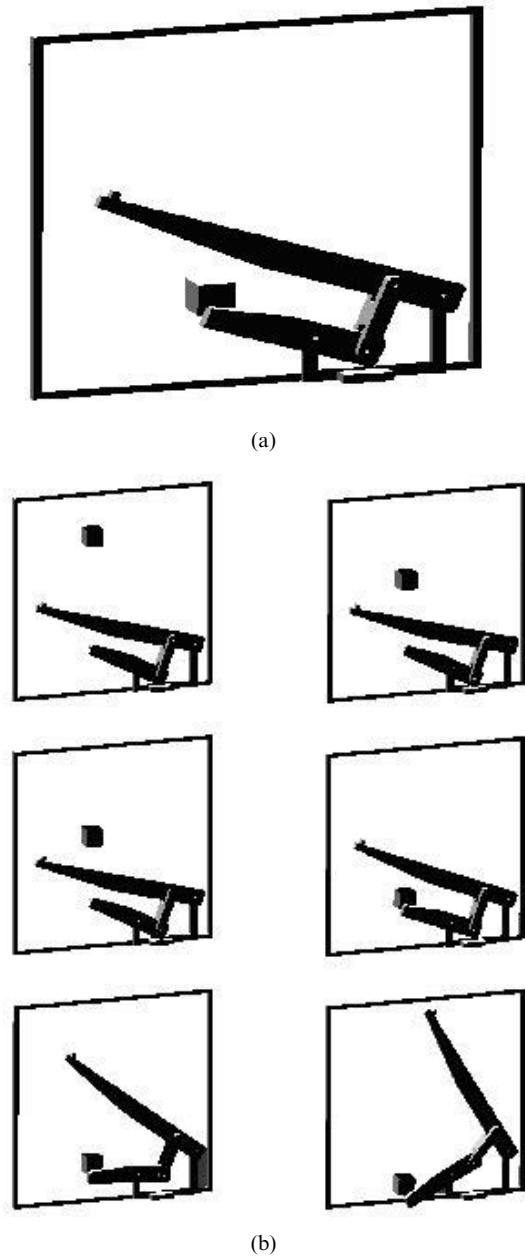
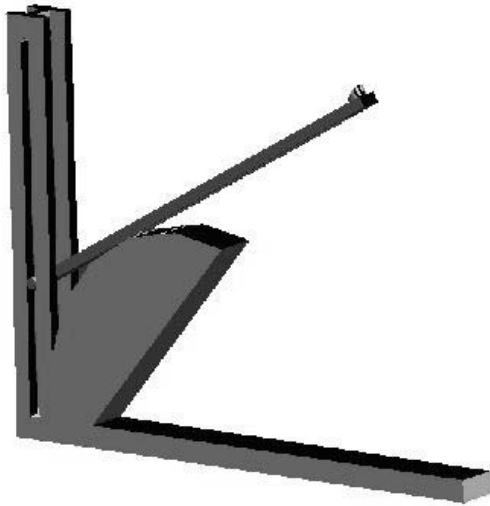
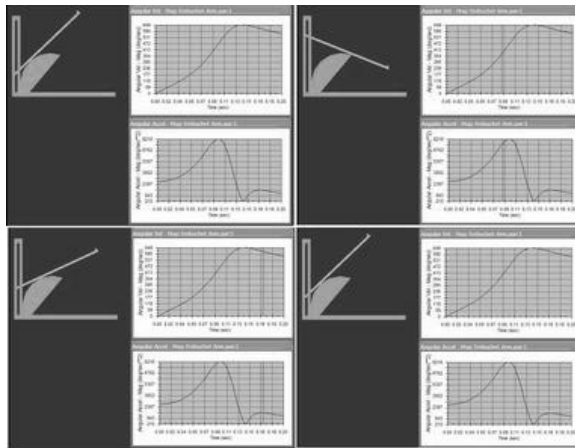


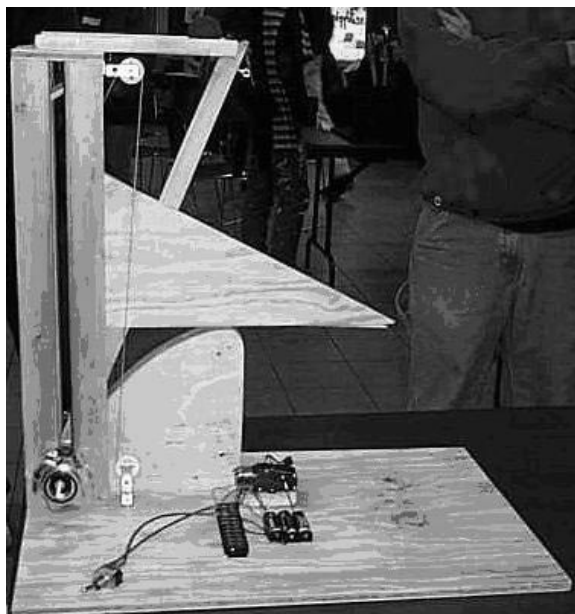
Fig. 7. (a) Virtual model of a catapult system using impact force to throw a squash ball, (b) virtual prototype in action, (c) physical model.



(a)



(b)



(c)

Fig. 8. (a) Virtual model of a catapult system using modified cam design, (b) virtual prototype in action with plots, (c) physical model.

the computational power required by the tools and the accuracy of the results.

PHASE-III TUTORIAL CASE-STUDIES

In the third phase, the students are required to design and build a mechanism (at least a four-bar) to accomplish two distinct sets of objectives in their task specifications. The first objective is to design this mechanism to launch a squash ball the furthest distance, while the second objective emphasized precision shooting of the squash ball into a basket. Other limitations on actuator sizes, overall dimension and material used are also given to constrain the problem further.

The students were required to follow the creation, testing and refinement cycle as shown in Fig. 1(b) above with their virtual models. This gave the students an opportunity to create a VP from scratch, to better understand the design process and how the parameters affected the output and interactively refine their designs to meet the specifications. The results of this analysis were then prototyped physically; the emphasis was on being able to match the physical performance to the prediction in the VP process. Fig. 7 and 8 show examples of the VP and corresponding physical prototypes built by the students in the first offering of the course. Selected videos showing the comparisons of both prototypes are available on the course website [29].

DISCUSSION AND CONCLUDING REMARKS

Based on experience from the offerings of these tutorials, we note that the students had some initial difficulty but are able to create virtual prototypes and use them to refine their catapult designs before building physical prototypes. Most of the feedback highlighted the need for more time to use these tools effectively while noting the usefulness of the tutorial.

From the instructional viewpoint this proved to be a viable vehicle for bridging the gap between conventional classroom-based approaches for teaching mechanisms and an experiential approach. In terms of instructional support, very little is required to support the course (after the initial investment of effort and time in the tutorial).

The level of detail in the step-by-step instructions is a factor that we will be investigating further in future work, in some of which we plan to increase gradually the number and complexity of intermediate 'mini-projects' to permit the students to get hands-on practice in engineering problems with different levels of complexity. A careful quantitative evaluation of the effectiveness of these tutorials is being considered as part of a study being conducted with other collaborators in the Educational Multimedia Studies program at UB.

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