Interactive Dynamics: A Collaborative Approach to Learning Undergraduate Dynamics

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Abstract

Collaborative learning, computer simulations and practical experimentation are the essential elements of a new project for the enhancement of undergraduate engineering courses currently being developed at Penn State University. This project introduces teamwork, hands-on activities and visualization in courses traditionally containing none of these. The approach used to implement these innovations into a sophomore level dynamics course is described. A discussion of the most significant issues and hurdles encountered during this implementation is included so as to assist other educators in designing learning environments like the one presented here.

1 Introduction

Engineering graduates are increasingly required to become immediately productive in the workplace without the on-the-job training that was typical of recent decades. Among other things, this requires the development of team skills along with a high level of computer literacy. These skills have not only been considered more and more important by industries but also, at least in the United States, by accreditation boards, such as ABET, and agencies, such as NSF. In fact, the strategic goals set for engineering education institutions by ABET, stated in a recent report entitled “ABET Criteria 2000” [2–5], include

- the ability of applying knowledge of mathematics, science and engineering;
- the ability to apply advanced mathematics in engineering problem solving;
- the ability to design and integrate contemporary analytical, computational and experimental practices;
- the ability to work in teams and to effectively communicate

as standard skills to be mastered by students by the completion of their undergraduate degree. The demand for team and computer skills is clearly at odds with what is commonly found in most undergraduate engineering curricula. In fact, many of the studies in engineering education have identified, among other things, the lack of hands-on laboratory experience, multi-disciplinary or systems perspective, understanding of information technology, and understanding of the importance of teamwork as shortcomings of most of the current curricula [1–8]. Also, the complex set of skills summarized above cannot be provided by a few courses in an engineering curriculum. Ideally, the ability to work in teams and to use the computer as a platform supporting interdisciplinary integration and communication should be cultivated in students from the very beginning and throughout the undergraduate experience. It is, therefore, crucial that courses be developed which integrate teamwork, computation, data acquisition, data analysis, and information technology into the very process of learning.

In reference [9] the current authors have presented a new approach to addressing the problem of how to introduce all the elements mentioned above into sophomore/junior level courses. The approach in question has been dubbed "Interactive Mechanics" and has been practically implemented into the first engineering dynamics course offered at Penn State (we call this course Interactive Dynamics). In this paper, after a brief summary of the Interactive Mechanics approach, the practical considerations associated with implementation of this approach in undergraduate mechanics courses at Penn State University are discussed in detailed, with particular attention to issues concerning the use of collaborative learning.

2 Interactive Dynamics

We now briefly describe Interactive Dynamics, that is, the "dynamics" version of Interactive Mechanics. We begin by looking at the traditional course as a contrast.

2.1 The Traditional Dynamics Course

In the traditional "chalk and talk" mode of teaching undergraduate dynamics, an instructor presents three weekly, one-hour lectures in which he or she may have 5–10 minutes of interaction with the students in the form of questions and answers. During this one-hour lecture, the students' role is essentially limited to note taking. Therefore, in this type of learning environment there is little or no use of

- computers in or out of the classroom;
- team work;
- writing skills;
- hands-on or laboratory experience.

On the other hand, the low level of interaction between instructors and students makes the overall learning environment in which the students are placed a familiar, non-demanding and, therefore, comfortable one.

2.2 The Interactive Dynamics Course

Similar to a traditional dynamics class, Interactive Dynamics uses traditional "chalk-and-talk" lectures 40–50% of the time. It is the other 50–60% of the class that profoundly differentiates Interactive Dynamics from traditional dynamics, and we will refer to one of those distinguishing class periods as an Interactive Dynamics class. An Interactive Dynamics class typically begins with a 15–45 minute introductory lecture in which the goal of the day's *activity* is presented. This introduction is intended to point out any particularly important things the students should look for during the activity and to put that activity into a proper engineering context. After the introductory lecture, the activity begins.

An activity is in essence a project which requires the solution of a difficult problem. The level of complexity of these problems is such that team work is absolutely essential in order to complete the activity in the allocated time. In fact, activities are substantial enough such that they cannot be completed in one class period (the course meets two times per week for 1 hour and 55 minutes each time) and their completion almost always requires students to meet outside of class. Furthermore, along with team-work, computer tools and a written report are essential elements of any activity. Students are not "taken by the hand" as they work their way through each activity. In fact, we try to make the process of completing each activity to be as "real-world" as we can make it. In this sense, the students are the active element in their education and the instructor plays the role of listener, mentor, and advisor.

Within each activity, the notion that dynamics is about equations of motion and finding loads on systems for the purpose of design in strongly emphasized. In addition, each activity requires the students to work in teams and to either take on or assign roles for each of the team members. This requires communication, leadership, and management skills that are typically not required of students in the first dynamics course. Finally, Interactive Dynamics introduces its students to an abundance of concepts and ideas that students in a traditional dynamics course never see. For example:

- Although knowledge of ordinary differential equations is not a requirement for the course, the students are introduced to the language of ordinary differential equations and simple numerical methods for solving them (*e.g.*, Euler's method).
- Numerical derivatives are presented along with a discussion of the various numerical errors accompanying the use of numerical differentiation.
- Students are introduced to trajectories of differential equations and how to visualize and study their behavior.
- Students are introduced to the concept of equilibrium and steady-state solutions, ways of finding them, and ways to interpret them.
- With every activity, correct technical report writing skills are emphasized.

Again, all of these elements are intended to make the Interactive Dynamics classroom an environment which is as close as possible to the workplace that the students will experience when they leave school.

2.3 The Structure of an Activity

A class period containing an Interactive Classroom activity will typically begin with a 15–45 minute introductory lecture in which we present the goal of the day's activity and point out any particularly important things the students should look for. After the introductory lecture, the activity begins.

2.3.1 Numerical Solution of Equations of Motion

This activity emphasizes a point that is not often made in the first course in dynamics, namely that dynamics is about equations of motion and the motion over an interval of time and not about the motion at a specific instant in time. This activity is purely "analytical" in nature and shows the students that within the first three or four weeks of the course they have the ability to derive equations of motion describing complex systems and that, with a little effort, they have the ability to numerically solve these equations to make predictions about the motion.

We begin class by doing an example problem whose solution requires the derivation and solution of an equation of motion. We convince the students that the equation we have derived is not solvable analytically and that we must resort to some other means. This provides for a transition to the numerical solution of differential equations of motion and Euler's method. We then spend 30–40 minutes introducing Euler's method and Heun's method, which is a modified, more accurate version of Euler's method. After this is done, the instructor and every team in the class open their web browsers to see the activity.

The activity is presented entirely via the web within a browser. It begins with a short introduction to scientific computing with some interesting links to other web sites (in this activity, this includes links to sites such as the *The Computer Museum* at `http://www.tcm.org/` and the *NIST Guide to Available Mathematical Software* at `http://gams.nist.gov/`). It continues by paralleling our lecture, that is, by helping students understand what "equations of motion" are and helping them see that most equations of motion cannot be solved analytically. The activity then points out that all is not lost and that there are ways of approximating the solutions to these equations.

We then present two problems to the students:

1. A two degree-of-freedom elastic pendulum, and
2. A two degree-of-freedom system consisting of a mass on one end of an elastic rod, the other end of which is pinned. The system slides in the horizontal plane on a viscous layer and is undergoing a constant torque at the pinned end. It is just a modified version of the elastic pendulum.

2.3.1.1 An Elastic Pendulum

For this part of the activity, the students are given the appropriate physical parameters of the system in the following statement (also see Figure 1):

> The 0.25-kg mass, which is attached to the elastic rod of stiffness 10 N/m and undeformed length 0.5 m, is free to move in the vertical plane under the influence of gravity. The mass is released from rest when the angle $\theta = 0°$ with the rod stretched 0.25 m. Assume that the rod can only undergo tension and compression and that it always remains straight as the pendulum swings in the vertical plane.

We then ask the students to

1. Derive the equations of motion for this system and state the initial conditions.
2. Solve the equations numerically from the time of release ($t = 0$) until $t = 10$ seconds.
3. Find the maximum speed of the mass during this period of integration.
4. Determine the maximum value of R and the *first* value of θ theta when the rod becomes slack.
5. Plot R and $\dot{\theta}$ versus θ.
6. Plot the *actual trajectory* of the mass as you would see it for $t = 0$ until $t = 10$ seconds.

Parts 2–6 of this activity are all performed in Microsoft Excel. To do this, the students set up

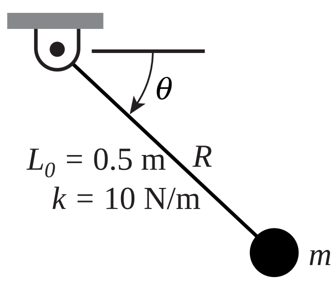

Figure 1. Diagram illustrating the elastic pendulum described in the activity.

columns in Excel defining position, velocity, and acceleration at each time step. They then use the equations for either Heun's method or Euler's method, along with the governing differential equations, to propagate the solution forward in time. This is easily done in Excel as one can simply drag down rows of numbers to update cells based on defined equations.

2.3.1.2 A Whirling Mass in a Horizontal Plane

As part of the same activity in which the students analyze the elastic pendulum, they also analyze a two degree-of-freedom problem described in the following statement:

With reference to Figure 2, consider a mass of 0.25 kg sliding on the horizontal surface forming the *xy*-plane. The surface is covered by a film of lubricant intended to facilitate the sliding motion, but which also provides a viscous resistance to the motion. The action of the lubricant on the moving mass is equivalent to a viscous resistance force, which is proportional to the velocity of the mass and has a viscosity coefficient $c = 0.3$ N·s/m. The mass is connected to the (fixed) origin of the *xy*-plane via an elastic rod which has a free length L = 0.5 m and elasticity constant k = 100 N/m. The rod can elastically extend but cannot bend. The mass is acted upon by a force F = 5.0/R N oriented always in a direction perpendicular to the rod, where R is the length of the rod. From a physical viewpoint, the force F results from the application of a constant moment of magnitude 5.0 N·m applied to the elastic rod. At time t = 0, the mass is at rest with an initial position characterized by R = 0.1 m and y = 0.

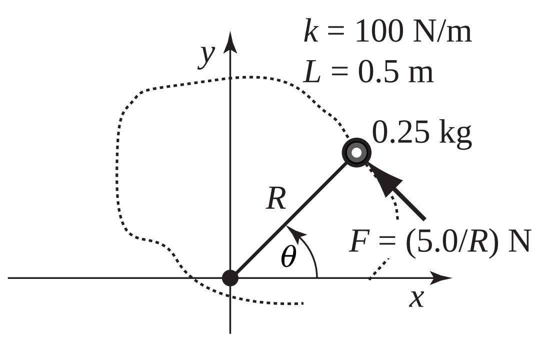

Figure 2. Material point sliding on the *xy*-plane while attached at the end of an elastic rod.

We then ask the students to perform the following tasks:

1. Derive the equations of motion and state the corresponding initial conditions.
2. You will discover that after some time this system will be characterized by a circular motion with constant angular velocity. For convenience (and because this is how engineers refer to it), this part of the motion will be referred to as the *steady state* solution. Analytically (*i.e.*, without using computer solutions) determine the radius of the circular trajectory and the corresponding value of the angular velocity for the steady state solution.
3. Numerically integrate the equations of motion to compute and then plot the trajectory of the mass during the interval of time $0 < t < 5$ s. Verify that the trajectory will, at some point, coincide with the circle determined in Item 2.
4. Finally, repeat the operations done in Item 3 for other two sets of arbitrarily assigned initial conditions and help verify that, regardless of initial conditions, the motion of the mass

will converge to the steady state solution. Provide a physical explanation for this behavior.

2.3.2 Pedagogical Benefits of this Activity

This activity reinforces and gives the students practice in the application of Newton's second law in polar coordinates and demonstrates the "equation of motion" nature of dynamics. In addition, even though a course in ordinary differential equations is not a prerequisite for undergraduate dynamics at Penn State, the students are given a thorough introduction to the language of ordinary differential equations (*e.g.*, dependent vs. independent variables, order of the equation, linearity vs. nonlinearity, coupled vs. uncoupled, initial conditions). Finally, the students are exposed to topics that are not typically covered in an undergraduate dynamics course:

- numerical analysis and the idea of different types of numerical error;
- trajectories of differential equations and how different types of plots can be used to study and visualize their behavior;
- steady-state solutions, ways of finding them, and their physical interpretation;
- correct technical report writing skills, with an emphasis on structure, writing precisely, and what to include in a technical report.

2.3.3 A Few Remarks

The essence of the Interactive Classroom is the *activity*. Activities, even when simple in concept, require a great deal of planning. In fact, several diverse issues often arise and need to be confronted before an effective implementation of an activity can be found. One of the most important of these issues concerns the type of software used in class. The following questions were used as criteria to choose software to be used by the students:

1. How useful will the software be to the student after he or she graduates? That is, is the software used extensively in industry?
2. How prevalent is the software on our university campus?
3. Is the package available on all of the most popular platforms?

In answering these questions, the authors' experience and that of other faculty in the College of Engineering as well as that of industrial liaisons who visit the authors' department every year was used as a guide. Microsoft Office was chosen as the "productivity suite" of applications, that is, for word processing, spreadsheet, and presentation applications. Microsoft Office is widely available at Penn State, is used almost exclusively in industry, and is available for both Windows and Mac OS. For "analysis" packages, MATLAB and Mathematica were chosen. Again, both packages are cross-platform and MATLAB, especially, is used widely in industry. Mathematica was chosen for its symbolic capabilities that are only available in MATLAB if one purchases an additional Toolbox. Finally, even though it is not used widely in industry, VideoPoint was chosen to analyze QuickTime movies since it is also cross-platform and allows us to perform some "virtual" experiments that would otherwise not be possible.

Another important issue that must be confronted when the class is working on an activity is that of staff support. In fact, students often have questions that require a great deal of attention on the part of the instructor. Also, questions from the various teams do not usually come in a streamlined fashion and are often posed simultaneously by various groups. Hence, it is rather difficult for a single individual to successfully assist all of the teams at once. To adequately assist roughly 10 to 12 teams, a minimum of two persons is required, although one instructor per 4–5 teams could be considered an optimal situation. Clearly, having two full-time faculty teaching the students in one class may be a heavy burden for a department to bear. The solution adopted in Interactive Dynamics consists of utilizing the help of properly trained undergraduate teaching interns. These are students who choose to include teaching in their undergraduate experience. The teaching interns gain credit toward the completion of their degree program and, at the same time, receive salaries which are usually not difficult for a department to provide on a regular basis.

3 Interactive Dynamics and Collaborative Learning

We now describe, in detail, some of the problems we have encountered, the issues that have arisen, and the hurdles we have overcome in implementing our Interactive Mechanics course. We describe all of these things with the purpose of giving other educators the benefit of our experience when implementing this educational concept or one similar to it.

3.1 Assembly of Teams

In Interactive Dynamics, we like teams to consist of three students. This requirement is motivated by the fact that the amount of effort necessary to complete an activity in the assigned time would be overwhelming for just one or two students. When the total number of students in the class is not divisible by three, teams of four persons are formed, four being the maximum number of students in an Interactive Dynamics team.

Teams are formed by the instructor during the first week of classes and are intended to remain fixed throughout the duration of the course. In order to facilitate the formation of the teams, a survey is conducted on the first day of classes. This survey requires students to self-assess their (*i*) mathematical proficiency, (*ii*) verbal as well as written communication skills, and (*iii*) level of computer literacy or familiarity with some of the software that will be used in class during the course. Hence, teams are formed in such a way that each of them contains at least one member familiar with one of the skill areas mentioned above. Despite this process, it was observed that teams still lacked the desired breadth of skills. A reason for this is the over-confidence with which students tend to self-assess their own skills. For this reason, in the future the team assembling process will also include the students' grade point average as an additional element to be used in the team assembly process. Another element that may help in giving teams a uniform amount of "motivation" is the students' majors. Engineering Dynamics, *i.e.*, the course that Interactive Dynamics is intended to improve, is a required course for most engineers at Penn State. However, not all majors perceive the Engineering Dynamics course content as useful to them in their engineering careers. This often causes a non-negligible number of students, randomly distributed among the various sections of the course, to view the course as a “necessary evil” that they have to endure in order to graduate. By including in teams members whose major requires the course as the basis for further curricular developments (*e.g.*, Mechanical or Aerospace Engineering), we hope that a healthier degree of “perceived interest” in the course is fostered.

3.2 Teams and Collaborative Learning

The course has been structured to invite the students to use a collaborative approach not only during activities but also during the solution of homework problems. Every week we assign a homework set consisting of three challenging problems. Although no specific instructions are given to the students on how to manage their homework assignments, we do require that each student turn in his or her own solutions. The incentive toward a team approach to homework solving consists of offering each team 5 extra points if their average grade on that homework assignment exceeded 90 out of 100 points. The intention is for each team to work together on the three problems so that they can learn from one another. This offers to each team member the opportunity to check their own work and that of the other team members. However, it was found that this initiative was only mildly successful in fostering a collaborative approach to these homework problems as a nontrivial number of students simply copy some or all of the problems from one or more of their teammates.

Teamwork plays a vital role in the completion of the activities. We have also encountered a number of hurdles in this arena. In particular, we have found that the biggest problem we have encountered is a lack of effort and responsibility on the part of a small number of students. In fact, for a team to be successful, two conditions seem to be necessary. First, it must be relatively easy for the students to gather outside of class to work on the activities (as well as homework), and, second, they must be mature enough to respond to the idea that the contribution of each affects the grade of all of the team members. These considerations lead to the conclusion that the students should be given the opportunity to coordinate (if not complete) as much of their team work as possible in class (although this may not be feasible depending on the amount of material one needs to cover in class). Furthermore, special attention must be devoted to the establishment of a grading policy that penalizes those who do not contribute, without discriminating against those students who, despite their efforts, are receiving a poor team grade due to lack of care of others. A discussion of the grading policy adopted in Interactive Dynamics is presented in the next section.

3.3 Distribution of Credit when Grading

The overall grade assigned to each student is the result of his or her performance, both as an individual and as a team member. The student’s individual performance is measured via traditional exams. Specifically, three exams are administered in addition to a final exam. Each of the three in-semester exams contributes 10% of the overall grade and the final exam contributes 20% to the overall grade. Each of the in-semester exams consists of three or four problems. All but one of those problems are usually traditional problems along the lines of those assigned as homework. One of the problems often focuses on testing the students on some of the material dealt with during group activities. Hence, individual performance amounts to 50% of a student final grade, thus leaving the remaining 50% to be gained through team-related work. In particular, 38% is associated with team activities and the remaining 12% is associated with the homework problems (though we should note that the homework problems could be done individually).

The overall grade breakdown described above is motivated by the fact that students spend the majority of their "Interactive Dynamics time", whether in or outside of class, dealing with team related work. Furthermore, the types of issues that must be confronted during an activity are often too complex to be formulated as problems on an in-class exam. Having said that the overall grade is structured to reflect the proportion of time spent dealing with team activities, it must also be said that this grade breakdown presents some potentially serious shortcomings. First, it should be noted that it is possible for a student to get 100% on all of the exams and, at the same time, to fail the course if no team related credit is earned. This basic observation, whether or not accompanied by considerations concerning the experimental nature of Interactive Dynamics, is at odds with how the traditional sections of Engineering Dynamics are managed. Hence, it is possible that some students, especially if very bright and independent, might complain that their overall grade is actually being negatively affected by the team activities. This problem takes on pathological proportions if a bright student happens to be on a "dysfunctional" team in which the other team members are not pulling their weight. Similarly, it is possible for a mediocre or a poor student to receive a good grade thanks to the work of others.[1] Hence, in order for this grading policy to reward hard work and good work it must be complemented by the instructor's discretion in assessing who is actually doing the work during the team activities. For this reason, the 50% of their grade, which is associated with team activity, is actually referred to as the Individual Activity Grade (IAG) and this differs from what we call the Team Activity Grade (TAG). The TAG, which is the same for each member of a team, is the grade given to any activity report or homework. Each student's IAG is determined using the simple relation that $\mathrm{IAG} = \mathrm{TAG} \times \mathrm{IAF}$, where IAF refers to an Instructor Assessment Factor and it is a number ranging from 0 to 1.25. Setting to 0 the IAF lower bound is intended to serve as a deterrent against "free-loaders". The IAF upper bound, set to 1.25, has been chosen to indicate that the instructor does not have "absolute power" in increasing the grade of an individual. This limit to the instructor's power is intended to be a deterrent against those students who may dislike teamwork, up to the point of "sabotaging" their team and relying solely on their exam scores. The IAF is chosen based on our observation of students and teams during the semester and on confidential peer evaluations that are completed by each student at the end of the semester. The peer evaluations allow each student to evaluate the work of his or her teammates and to comment on the fairness of the division of labor during collaborative work. With all of this mind, we should mention that for most students, the IAF is chosen to be unity.

The grading policy described above is rather complex, and it relies heavily on the instructor's awareness of the work ethic and "sociological health" of each of the teams. It should be mentioned that as of the spring 1999 semester, we are only in the third semester of teaching Interactive Dynamics. Thus, it has not been taught long enough to assess the effectiveness of this grading scheme and, for this reason, no claims are made to its fairness or success in promoting col-

[1] On the other hand, part of the motivation behind the inclusion of teams in Interactive Mechanics is the idea that teams help good students by putting them in an environment where they "teach" poorer students and teams help poorer students by putting them in an environment in which they are being helped by the better students.

laborative learning. In fact, we continue to refine the grading policy each semester. To date, we can only report that a fair and honest grade has been assigned to the students who have taken this course and that this grading policy has allowed us, the instructors of Interactive Dynamics, to resolve every controversy that has arisen within the various teams.

3.4 Presentation of Results

Almost every activity culminates for each team with the creation of a written report. From an educational viewpoint, these reports are intended to instill in the students the idea that good communication skills, written communication in particular, are extremely important in the engineering profession. From a more technical viewpoint, these reports are intended to impart in the students a few basic ideas on how to logically present the material they were supposed to have learned. Also, we hope that they will learn how to read a report and decode the information contained therein. The creation of a technical report also forces the students to think deeply about their results and to interpret them before going on to their next task. In order to facilitate this learning process, the students are supplied with a Microsoft Word template created by the instructors. This template is also a sample report structured in 5 basic parts: (*i*) an abstract, (*ii*) an introduction, (*iii*) a methods section, (*iv*) a results and discussion section, and a (*v*) conclusions section. If necessary, appendices are used to describe additional material that would otherwise make the body of the report difficult to read. It should be noted that giving so much structure to the activity report helps each team breakdown the overall report writing effort into simpler tasks that can be divided among the team members. In this sense, a highly structured activity report helps in improving the team skills of the students.

Since we have provided the students with this template, the main effort that is required of the students is that of creating the content of the sample report rather than having to focus on the format. On the other hand, since they have been provided with a professionally formatted report, it is hoped that they will learn by example what a report should look like and what it should contain. As part of this, the students are required to present their results using graphs and tables that must be formatted and displayed in a professional style. For example, one of the "phenomena" that the authors have observed in first time report writers is sentences like "… as can be seen in the figure, *A* follows from *B* …" when the none of the figures in the report are numbered or provided with a caption, nor does the information discussed in the text appear in any of figures displayed. We hope that we can give the students an appreciation of why this is wrong.

The emphasis of Interactive Dynamics is not, and should not be, on writing since it is not a writing-intensive course. Thus, the emphasis placed on the report style is minor when compared to the emphasis placed on the dynamics content of the activity problems. In other words, the students are left to learn about report writing from the example provided by the template given to them at the beginning of the semester and from the feedback given them when we grade the reports. For this reason, the template not only contains a sample report written by the instructors but it also contains a succinct report grading scheme which outlines the various sections of a report, giving a synopsis of their intended purpose as described in a manual of technical writing style being used at Penn State [10]. From a grading viewpoint, regardless of how badly written a report may be, more than 65% of its grade value is usually given to the students as long as the results reported are correct.

4 Conclusions

In a previous publication [9] we have presented the theory and pedagogical philosophies behind the Interactive Mechanics concept. In this work, we have presented some of the details associated with implementing a new teaching philosophy such as this. In doing so, we have tried to address many of the issues and questions that would arise if a faculty person at another college or university were to teach in this "interactive" way.

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