AC 2010-1641: TEACHING AUTOMOBILE, FLIGHT AND SYSTEM DYNAMICS USING INNOVATIVE MOTION SIMULATION EXPERIMENTS

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Abstract

This paper discusses the design and extension of a set of motion simulation experiments and their subsequent incorporation into an innovative framework to teach engineering systems analysis and flight dynamics, including topics such as system control, stability, feedback, and design. These are fundamental concepts at the core of many engineering systems including mechanical, aerospace, electrical, thermal, and fluid systems. Many engineers are increasingly turning to simulation and virtual prototyping, rather than physical prototyping, to explore new design concepts. As the use of simulation increases across all of engineering, the demand for students with hands-on experience in configuring, executing, and understanding simulation-based experimentation will also increase. In this paper, we present the results from integrating experience-based system simulation modules into a series of vehicle dynamics courses. We also present experiential modules to integrate the motion simulation system into a required junior-level mechanical engineering course and in a required senior-level flight dynamics aerospace engineering course. This paper reports on work done under National Science Foundation grant DUE-0633596 in the Course, Curriculum, and Laboratory Improvement (CCLI) program.

1 Background and Motivation: Cyber-enhanced Education

In engineering education, relating theoretical and analytical results to real-world phenomena is one of the most difficult tasks. While text, equations, diagrams, and graphs are an efficient means of presenting large amounts of information, such representations are, necessarily, abstractions of reality. A significant portion of a student's learning process is learning how to transform these abstractions into knowledge that will allow them to apply their understanding to real-world products and systems. Many attempts to bridge this gap are employed by educators, including in-class demonstrations, laboratory experiments, videos, and computer graphic simulations¹⁻⁴.

In a study of the application of information technology to education, the President's Information Technology Advisory Council⁵ recommended the development of technologies for education and training that use simulation, visualization, and gaming to actively engage students in the learning experience. In the same report, PITAC also recommended the development of educational experiences that provide learners with "access to world-class facilities and experiences using either actual or simulated devices". The benefits of imitating a real process by way of simulation cannot be understated. The educational value of simulations does not necessarily lie in the program itself, but rather, in the overall experience of the simulation⁶.

Using a simulated digital environment to supplement traditional instruction is not a new concept. Early attempts to understand the role of digital environments in workplace instruction demonstrated the potential of computer simulations acting as a cognitive apprentice⁷. The use of virtual laboratory environments to replace or supplement physical experiments in engineering education emerged soon after that. Virtual laboratory experiments were created to supplement the physical laboratories to teach various electronics and circuitry concepts⁸. Both quantitative

and qualitative results strongly supported the use of the virtual experiments as a supplemental source of learning. Baher created a virtual laboratory to provide students with more and quicker access to feedback on the thermodynamic performance of their virtual and simulated design concepts⁹. Studies across three universities demonstrated potential to provide valuable additional instruction to students using the virtual simulations. Other simulated environments have been developed to enhance or replace the traditional physical instruction of a number of engineering topics including nuclear magnetic resonance spectroscopy¹⁰, unit operations¹¹, system dynamics¹², ultra-precision machining¹³, and strength of materials¹⁴.

While the associated educational strategies and relative effectiveness are still being developed and studied, there would seem to be a synthesis between cyber-enhanced engineering education and the social culture of today's engineering students. The current generation of engineering students is defined by the digital culture they create and in which they live¹⁵. While most students are familiar with the use of digital tools for everyday applications, it is natural to wonder if educators and researchers in the engineering fields can and should capitalize on the emerging multimodal digital literacies to facilitate pedagogical goals. In this paper, we present the implementation of an innovative digital environment and set of experiments for coupling motion simulation and educational practices together in an engaging, learner-centered approach.

2 Cyber-Enhanced Implementation: Dynamics Education

The theory of vehicle dynamics is familiar to all students in an engineering curriculum, in that everyone has either driven or been a passenger in an automobile. Thus, vehicle motions are inherently familiar to the student. Also, with over 40 million vehicles being manufactured each year worldwide¹⁶, advances in computing technology and vehicle systems have expanded the influence engineers have over the stability and control of vehicle dynamics. Augmenting systems such as anti-lock brakes, electronic skid prevention, yaw control, active differentials, and similar "active" vehicle design systems improve safety and performance over traditional passive designs. This increased control over the automobile will soon be inseparable from the increased complexity of the subsystems, all of which will combine to determine handling characteristics of the automobile. As a result, engineers are increasingly turning to simulation and virtual prototyping, rather than physical prototyping, to explore new design concepts. As the usage of simulation increases, the demand for students with hands-on experience in configuring and executing simulation-based research will also increase.

In addition, many engineering students have experienced controlling a sophisticated driving or motion simulation environment in the form of digital game-based driving or flight simulators such as the Wii, PS3, or Xbox gaming platforms or more realistic driving simulation platforms¹⁷⁻²¹. However, they do not necessarily associate the gaming environment with the models, equations, and system dynamics that engineers employ to design the driven vehicle or aircraft. Yet, video games and gaming systems have increasingly been found in applications more diverse than just entertainment, including use in training, education, research, and simulation.

This emerging field of Serious Games²²⁻²⁴ is intended to provide an environment for an accurate and an engaging context within which to motivate participants beyond the capability of conventional approaches. Computerized simulations implemented expressly for educational

purposes, sometimes also referred to as “Edutainment”^{25,26}, can indeed be powerful tools for learning. They allow learners to: a) manipulate otherwise unalterable variables, b) view phenomena from new perspectives, c) observe large system behavior over time, d) pose hypothetical questions to a system, e) visualize a system in multiple dimensions, and f) compare simulation behavior with that of the “real life” system. By enabling students to interact directly with a model of a complex system (e.g. a driving simulation), simulations place learners in a unique position to understand a system’s dynamics.

Consequently, this paper presents the continued development and evaluation of a driving and flight simulation-based learning environment that provides an authentic and engaging context for mechanical engineering education. The framework presented in this paper is designed to promote hands-on student participation in authentic engineering experiences that enhance conventional learning mechanisms for systems analysis and flight dynamics. The approach leverages authentic off-road driving and flight simulation environments and incorporates real-time simulation and large-scale visualization. These experiences facilitate the student discovery of the impact that design decisions have on vehicle and aircraft design and the underlying scientific system dynamics and control principles that guide such design decisions.

The ideally authentic experience in vehicle dynamics education would be to have students drive real automobiles, perform specific driving maneuvers, use on-board instrumentation to collect vehicle data, and modify the vehicle to observe resulting changes in its characteristics. While not impossible, concerns about cost, time, space, safety, and weather constraints deem this option impractical at most schools. An alternative solution is, indeed, to make use of an authentic, simulated driving environment. While driving-game based approaches have been developed for mental health, driver workload, and rehabilitation applications²⁷⁻²⁹, gaming-based contexts have not, to date, been used in vehicle dynamics education. Accordingly, this paper presents the development of a motion simulation-based learning environment that provides an authentic and engaging context for dynamics education. In the next sections, we describe the development of the experiments and their implementation in automobile, flight and system dynamics courses.

3 Vehicle Dynamics Implementation

The hardware and software framework used to develop and implement the innovation cyber-enhanced experiential learning modules is more fully described in previous work³⁰⁻³². Briefly, the motion simulator consists of a six degree-of-freedom electrically actuated motion platform. The device accommodates two passengers in a front-seat vehicle passenger cabin – a 1999 Ford Contour vehicle that has been custom-outfitted for the laboratory. The driving passenger supplies inputs to the simulator using one of numerous controls, including a steering wheel, three pressure modulated/adjustable floor pedals, and six on-wheel real-time feedback buttons. Figure 1 is an image of the exterior of the vehicle cabin and frontward simulation screens, Figure 2 is a top view of all 4 simulation screens, and Figure 3 is a close-up image of the driver control panel.

The software framework that comprises our driving environment was developed entirely in-house, intended primarily for a single, multi-processor PC-based workstation. Figure 4 illustrates the overall schematic of the motion simulation facility including the computing, visualization, audio, motion processing, and control components.

Figure 1 – Motion Simulator

Figure 2 – Four Screen Arrangement

Figure 3 – Driver Control Panel

Figure 4 – Laboratory Schematic

This driving, flight, and motion environment has been used previously with substantial success in two upper level mechanical engineering electives in road vehicle dynamics. In previous work³⁰⁻³¹, the details of the implementation are given. The assessment in the previous work, while very positive, was based largely on student perception and impact on their education. In this paper, we present the impact on the instructor's educational objectives for the vehicle dynamics course.

3.1 Experiment 1: Set-up

The first experiment was created for undergraduate/graduate students in our Road Vehicle Dynamics 1 (RVD1) course (MAE 454/554). It is based on a simple circular test track known as a "skidpad". Skidpad testing is a typical automotive proving ground activity dating back to the 1930s³³. Two walls define the edges of our virtual world, with an inner radius of 50 feet an outer radius of 500 feet. Centered between the inner and outer walls is a 60 ft. wide circular strip of drivable track bounded by cones as illustrated in Figure 5. Note the top view of the track geometry in the lower-central portion of the viewport.

Figure 5 – Skidpad Experiment 1

Students were asked to drive vehicles with different configurations at gradually increasing speeds around the skidpad. They were also asked to comment on the amount of steering required to maintain their path and how easy it was to maintain their desired path. Multiple students drove runs lasting two to three minutes in duration. Data from each run was saved for later analysis by the students. A variety of vehicle configurations were driven, comprising of different center of gravity (CG) locations and different tire cornering stiffness distributions. Prior to the experiment the students knew what these two terms meant, but they had not yet been exposed to implications of the relationship between these two vehicle parameters.

Through the experiment students were expected to conclude that the front weight distribution (CG location) must exceed the front cornering stiffness distribution to achieve a stable vehicle. The opposite relationship produces unstable vehicles and, when they are equal, a neutrally stable car results. They were also expected to note that the unstable car could be successfully driven at low speeds, but became much more difficult as speeds increased. This is a result of the yaw damping effect which is very important in even the simplest vehicle dynamics models.

3.2 Experiment 1: Quantitative Educational Impact

Table 1 shows the pre-test and post-test items and related statistics. Through the experiment students were expected to understand the fundamental concept that the front weight distribution (CG location) must exceed the front cornering stiffness distribution to achieve a stable vehicle. The opposite relationship produces unstable vehicles and, when they are equal, a neutrally stable car results. They were also expected to understand that the unstable car could be successfully driven at low speeds, but became much more difficult as speeds increased.

Items 1 and 2 in Table 1 were graded with a partial credit rubric. A score of 2 points was given to a correct answer. A score of 1 was given to students who incorrectly identified the pairs either below (for item 1) or above (for item 2) the main diagonal. A score of 0 was assigned to all other answers. Items 3 and 4 were scored as 1 for correct items and 0 for incorrect items. The pre-test was administered to 44 students (all in attendance on that particular class) at the end of the large lecture class preceding the experiment class. The post-test was administered to 51 students immediately following the small group motion base laboratory experience. With the exception of the motion base laboratory experience, no other intervening instruction occurred between administrations of the pre-test and post-test.

Due to missing or illegible identification data, 43 paired samples were used in the statistical analysis. Significance for a nondirectional (2-tailed) t-test is shown using asterisks in Table 1. Since the pre-test data acted as the control for the study, the effect size was calculated by taking the ratio of the difference in the pre-test and post-test means to the standard deviation of the pre-test mean.

For items 1 and 2, the impact of the experiments on the students' understanding is clearly significant as the mean score jumps from 0.133 pre-test to 1.577 post-test ($p < 0.001$). For items 3 and 4, the impact of the experiments is still statistically significant ($p < 0.05$). These items are perhaps less significant than items 1 and 2 because it was easier to initially guess the correct answers for these questions. For instance, on item 4, the pre-test average score of 0.522 indicates that roughly half the class guessed "yes" (earned a score of 0) and half guessed "no" (earned score of 1).

Table 1. Pre- and Post-test Results: Experiment 1

Item administered on pre-test prior to motion base experience and then on post-test after motion base experience (n = 43)	Pre-test Mean (SD)	Post-test Mean (SD)	p-value	Effect Size
1. A car is driven at 65 mph. Circle all the <u>unstable</u> combinations of (cornering stiffness distribution %, weight distribution %) pairs				
(60, 60) (60, 50) (60, 40)	0.133 (0.457)	1.577 (0.750)	0.000	2.324***
(50, 60) (50, 50) (50, 40)				
(40, 60) (40, 50) (40, 40)				
2. A car is driven at 65 mph. Circle all the <u>stable</u> combinations of (cornering stiffness distribution %, weight distribution %) pairs				
(60, 60) (60, 50) (60, 40)	0.133 (0.457)	1.615 (0.718)	0.000	2.456***
(50, 60) (50, 50) (50, 40)				
(40, 60) (40, 50) (40, 40)				
3. Which of the following contributes <u>most</u> to the stability of a car? Circle one of the options and explain your answer.				
a. the weight of the vehicle				
b. the cornering stiffness distribution				
c. the weight distribution	0.556 (0.503)	0.923 (0.269)	0.043	.912*
d. the relationship between options a and b				
e. the relationship between options a and c				
f. the relationship between options b and c				
g. the relationship between options a, b, and c				
4. If a car is unstable, will you notice at low speeds? Explain your answer.	0.522 (0.503)	0.827 (0.382)	0.042	.416*

* Significance indicated as follows: * $p < .05$, ** $p < .01$, *** $p < .001$

3.3 Experiment 2: Set-up

The second, more advanced experiment for students in the RVD1 course makes use of the skidpad from the previous experiment and a simple race track that we refer to as the Tri-Radial Speedway. The dimensions of our virtual race track are double the size of the skidpad. Here, walls bound our world with an inner radius of 100 feet, and an outer radius of 1000 feet. The course consists of a large constant-radius left turn shortly after the starting line, followed by a tight constant-radius right turn, followed by a second large left turn that leads into the final straightway. Figure 6 shows a portion of this speedway. Note the top view of the track geometry (track map) in the lower-central portion of the viewport.

Figure 6 – Tri-Radial Speedway Experiment #2

The goal of this experiment is to investigate the new parameters in the more advanced vehicle dynamics model. As with Experiment 1, students took turns making two to three minute runs on the simulator, each with a specific vehicle configuration and driving task. Data was recorded for later analysis, and student driver feedback was immediately relayed and discussed by all students. Unlike Experiment 1, the CG location and tires models were held constant, with the tires being represented by a more advanced nonlinear tire model representation.

Most of the work was once again conducted on the skidpad, with students driving at ever increasing speed and noting how much steering was required, how stable the car felt and how easy/difficult it was to maintain the desired path. Each run was conducted with a different roll stiffness distribution, front roll center height or rear roll center height. Students were expected to conclude that increasing the front roll stiffness distribution, increasing the front roll center height or decreasing the rear roll center height all increased the vehicle “understeer” - when the vehicle does not turn as quickly as the angle of the front wheels would indicate.

Students also drove the advanced vehicle model on the Tri-Radial Speedway. Here, the goal was to drive as fast as possible while experiencing the friction ellipse and load transfer effects. Both of these were exaggerated to make them more apparent to the drivers. Students experienced how front and rear drive behaved differently when tractive effort was applied (as it reduced the lateral force on that end of the vehicle). They also experienced the destabilizing effect of heavy deceleration.

3.4 Experiment 2: Quantitative Educational Impact

Table 2 shows the pre-test and post-test items and related statistics. Note that item 1 was graded with a partial credit rubric, with a maximum score of 3. Item 2 was given a 1 for correct responses and 0 for incorrect responses. The pre-test was administered to 51 students (all in attendance on that particular class) at the end of the large lecture class preceding the experiment class. The post-test was administered to 52 students immediately following the small group motion base laboratory experience. With the exception of the motion base laboratory experience, no other intervening instruction occurred between administrations of the pre-test and post-test.

Due to missing or illegible identification data, 47 paired samples were used in the statistical analysis. Significance for a nondirectional (2-tailed) t-test is shown using asterisks in Table 3. Since the pre-test data acted as the control for the study, the effect size was calculated by taking the ratio of the difference in the pre-test and post-test means to the standard deviation of the pre-test mean.

For item 1, the impact of the experiments on the students' understanding is clearly significant as the mean score jumps from 1.608 pre-test to 2.615 post-test ($p < 0.001$). For item 2, the impact of the experiments is still statistically significant ($p < 0.05$) although it is easier to guess the correct answer for this question initially. The pre-test average of 0.529 on item 2 indicates that roughly half the class guessed "A" (earned a score of 1) and half guessed "B" (earned score of 0).

Table 2. Pre- and Post-test Results: Experiment 2

Item administered on pre-test prior to motion base experience and then on post-test after motion base experience (n = 47)	Pre-test Mean (SD)	Post-test Mean (SD)	p-value	Effect Size
1. Place an "X" next to the following changes which will <u>increase</u> a car's understeer gradient:				
___ Increasing front roll stiffness distribution				
___ Decreasing front roll stiffness distribution				
___ Front roll stiffness distribution has no effect				
___ Increasing front roll stiffness height	1.608	2.615	0.000	1.325***
___ Decreasing front roll stiffness height	(0.723)	(0.796)		
___ Front roll stiffness height has no effect				
___ Increasing rear roll stiffness height				
___ Decreasing rear roll stiffness height				
___ Rear roll stiffness height has no effect				
2. When additional throttle is applied in mid-corner, which configuration results in a stabilizing effect? Circle one:				
A. Front Wheel Drive	0.529	0.885	0.024	.839*
B. Rear Wheel Drive	(0.504)	(0.323)		

* Significance indicated as follows: * $p < .05$, ** $p < .01$, *** $p < .001$

3.5 Experiments 1 & 2: Qualitative Educational Impact

For the final two qualitative analysis questions on each post-test survey, an inductive analytical framework was used involving three general flows of activities: reducing the data, creating thematic categories, and drawing conclusions³⁴ through a data analysis spiral³⁵. The first qualitative question was given as “How well did this experience prepare you to answer items 1-4? Explain your answer.” For this question, 101 out of the 104 responses across both experiments thought that the simulator experience was helpful/positive and 2 people left the question blank.

The most frequent responses to the “Explain your answer” part of the question were as follows, where the thematic categories were derived from actual student wording:

- Helped me understand the concepts/ideas and their relationships
- Hands-on experience is helpful, allowed me to feel what was happening, able to feel the concepts, better able to understand something that you do
- Systematically able to compare ideas and refine our understanding, able to better understand impact of changes, different scenarios were helpful to develop ideas
- Tied theoretical knowledge to practical work
- Helped visualize the situation
- Interactive process helped me learn, dynamic experience better than lecture
- Real-world experience, actual examples
- Gave me experimental (objective) information, able to learn from the data
- Fun environment to learn

When an individual addressed multiple issues, each issue was categorized. Note that multiple rephrasings of the same idea are only counted as a single response in that category.

The second qualitative question was given as “Given a choice, would you prefer to learn the concepts covered during the experience using the motion base simulator or through a classroom lecture? Explain your answer.” For this question, 89 out of the 104 students selected the simulator experience as their preferred method to learn the concepts, 10 said that they would prefer both, and 5 responses were blank or illegible.

The most frequent responses to the “Explain your answer” part of the question were as follows, where the thematic categories were derived from actual student wording:

- Hands-on learning experience, tactile feedback important, able to feel the concept
- Easier to visualize what is happening, able to see how things interact
- More interesting/engaging/fun
- Closer to a real experience, easier to relate to real life, more tangible than lecture, felt realistic, easier to learn through actual experience
- Learn from modifications, able to see how model reacted under certain conditions
- More likely to remember, easier to remember what you experience, more memorable
- Helps unite theory and practice, see how concepts from classroom are put to use
- Easier to trust what you experience
- Quicker way to learn
- Interactive nature helped me learn

From the quantitative and qualitative data, it is clear that the students not only enjoyed the experience and found it beneficial, but they scored significantly higher on questions testing fundamental principles after the laboratory experience.

4 Current Implementations

4.1 Flight Dynamics

An important extension of the experiential learning framework includes modules for flight dynamics, which is a fundamental learning objective in all Aerospace Engineering curricula. Flight dynamics is the science of controlling position and orientation of an aircraft to ensure stable flight in three dimensions. The focus in flight dynamics is the relatively short term motion of an aircraft in response to controls or to external disturbances such as atmospheric turbulence. The dynamic behavior of an aircraft is shaped significantly by its stability and control properties which in turn have their roots in the aerodynamic characteristics of an aircraft. This leads to the derivation of mathematical models which describe the stability, control and dynamic characteristics of aircraft and are typically interpreted with the aid of computational tools.

In the current Flight Dynamics course at the University at Buffalo – SUNY (MAE 436), students are introduced to the performance, stability, and control of aircraft ranging from micro-uninhabited air vehicles through general aviation, jet transport, and fighter aircrafts. Particular attention is given to mathematical models and techniques for analysis, simulation, and evaluation of flying qualities, with brief discussion of guidance, navigation, and control. The course is required for the aerospace engineering program, and the typical enrollment in the course is approximately 65 junior/senior undergraduate students per year.

In traditional offerings of the class, the rigid body equations of motion are derived from first principles in class along with techniques to model the aerodynamic forces and moments acting on an aircraft. Further, reduced-order linear models are derived pertaining to longitudinal and lateral motion of an aircraft from complete set of aircraft equations of motion. Typically, students use Matlab-based computer programs throughout the course (as they do at UB) to analyze the static and dynamic stability characteristics of different aircrafts. Students have had difficulty developing an understanding of concepts such as the effect of center of gravity location on longitudinal stability of an aircraft, coupling between directional and roll stability, and the effect of static stability derivatives on dynamic modes of motion without physically experiencing them. The current Matlab program is a useful tool but is limited in that it only provides a graphical display of data, as opposed to a more elaborate simulation experience.

The proposed experiential learning module would address this gap through the creation of a series of guided inquiry-based exercises using either a modified version of the control panel in Figure 3, or the motion simulator laboratory at our new partner institution Buffalo State College. This simulator, shown in Figure 7, could provide the necessary hardware to run the modified vehicle dynamics software for flight dynamics experiments. By combining a flight simulator with an experiential environment where students can adjust aircraft's geometric and aerodynamic characteristics, students will be asked to discover many of these relationships. Animations and pre-configured simulations will be provided to allow a student to discover how each key concept relates to fly an aircraft. Restricted single degree of freedom aircraft motion would be

considered to enhance the understanding of key concepts pertaining to flight dynamics. This will permit the students to gain some experience in the mathematical representation and physical understanding of aircraft response before the more complicated multiple degrees of freedom motion are analyzed.

Figure 7 – Cessna Aircraft Simulator (courtesy of Dr. Jim Mayrose, Buffalo State College)

For example, a test case in which the aircraft's CG is constrained to move in a straight line at a constant speed but the aircraft is free to pitch about its CG would be considered to develop an understanding of the longitudinal motion of an aircraft. The students could be shown an animation of an aircraft pitching motion with varying degree of static and dynamic stability and will be made to experience the motion in the flight simulator. Later, students could be asked to control the pitching motion for different scenarios and provided with a series of challenges to allow them to discover the relationship of design parameters to airplane handling characteristics, such as:

- Moving the CG to obtain underdamp, overdamp and critical damp pitching response of an aircraft.
- Determining the elevator angle to trim the airplane for different CG locations.
- Determining how the pilot input can induce short or long-period dynamic modes of motion.
- Influence of horizontal tail area on the longitudinal response of an aircraft.

Students can then be asked to classify a set of airplanes by their handling characteristics using the Cooper-Harper scale³⁶. The simulation interface could record each configuration that the student uses as they tune the aircraft to their understanding of an optimized aircraft, providing the instructor with a formative assessment tool. Similar experiments will be designed to better understand the yaw and roll motion of an airplane, and analyses of airplane motion with multiple degrees of freedom.

Another important extension with significant broader impact is the implementation into a junior level systems analysis course. This course is a fundamental requisite course in any Mechanical or Aerospace Engineering curricula. Given the number of these across the nation, the impact of this kind of experiential module is substantial. A systems analysis course provides an ideal setting to use the motion simulator to teach systems concepts such as spring-mass-damper systems, natural frequencies, resonance, and stability.

Current work is focused on developing experiments using the environment shown in Figure 8. In the environment, there are a number of driving lanes with speed bumps placed at different frequencies. By driving in the various lanes, students will get to experience different input frequencies and output responses (vehicle behavior). These inputs and outputs can then be related to system stability concepts and plots. Vehicle spring rate and damping rate will also be varied to note the impact on stability using transfer functions. This experiment will utilize a gaming paradigm to challenge the students to achieve certain levels of performance based on their vehicle's response. This paradigm, while more experiential in nature in our planned implementation, is similar to the very effective gaming approach taken by Collier to teach a numerical methods course to mechanical engineering students³⁷.

Simulation has been used in many educational contexts, and is often used when it is too expensive or too dangerous to allow students to operate the actual systems. In such situations, students can instead spend time learning valuable lessons in a safe and authentic virtual environment. The convenience allows mistakes to be made and “what-if” scenarios to be studied

during training for a safety-critical system - such as a road vehicle or airplane - within which errors are not as permissible.

This paper reports on the continued developments and integration of a simulation-based experiential learning environment for various dynamic systems, including road vehicles, aircraft, and general electrical, mechanical, thermal, and hydraulic systems. Recent implementation in a road vehicle dynamics course demonstrated impact on the students' ability to understand key course concepts and in their perception of their own learning effectiveness. Developmental templates are also presented for flight dynamics and systems analysis courses. Additional future work includes desktop applications and multi-participant motion simulation by networking multiple motion simulation sites.

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