Game-based dynamic simulations supporting technical education and training

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***Abstract*—Educational games may improve learning by taking advantage of the new knowledge and skills of today's students obtained from extensive use of interactive games. This paper describes how interactive dynamic simulators of advanced technical systems and phenomena can be shaped and adapted as games and competitions supporting technical education and training. Some selected examples at different educational levels are shown, from vocational training to university level courses. The potential benefit and perceived learning effect of this approach is also described and underpinned from comprehensive user feedback.**

***Index Terms*—Dynamic simulation, games, technical education, web-based, elearning**

I. Introduction

Technical education, and especially engineering education faces a number of challenges because of the recruitment situation in many countries within the engineering domain. According to the International Council of Academies of Engineering and Technological Sciences, Inc. with member academies in over 25 countries, including the major countries, attracting young students into careers as engineers, technologists, or technicians is a serious problem [1]. Another citing describes the situation in the U.S. who has lost 25% of its undergraduate population in engineering between 1982 and 2000 [2].

Today's students have knowledge and skills from extensive use of computer or video games, or more generally interactive game software [3]. A computer game is in principle a game composed of a computer-controlled virtual universe that players may interact with in order to achieve a goal. Characteristics of such games are a high degree of interactivity, advanced graphics, a highly dynamical virtual universe, and an incentive system to promote prolonged and more advanced use. Computer games are quite diverse and can be subdivided into genres like action games, adventure games, arcade games, strategy games, puzzle games, racing games, role-playing games, classic games, and massive multiplayer online role-playing games (MMORPG). Typically the younger generation has solid experience from several of these game categories. Prensky [3] provides an in-depth discussion of the fact that the students have radically changed in the sense that they think and process information differently from predecessors. Today's students have grown up with computers and computer games, and Prensky [3] refers to them as digital natives since they can be viewed as "native speakers" of the new technology.

There is a growing understanding that educational games may create a new and improved learning culture [4]. New models that integrate learning theory and educational games are emerging [5], [6], and also learning resources based on such models are materialising [7]. In this paper we demonstrate the use of dynamic simulation-based games in this context.

II. Simulations and Games for Learning Purposes

The development of ICT solutions has allowed for more complex and advanced representations of learning material. In this context, dynamic simulators can be regarded as a further development of visualisations driven by mathematical models, and with a high degree of user interaction.

The visual packaging of online learning resources is important and a parameter that influences the learning effect of an elearning resource. To exemplify, the visual image of an elearning resource is shown in Figure 1. The graphitti-inspired image may seem strange to a mature audience. It has, however, been very well received by present undergraduate students as will be discussed later.

The concept of a highly dynamical virtual universe may come in conflict with conveying complex concepts in science and technology. We will nevertheless create a dynamic universe and in particular utilise dynamic simulators when appropriate. A dynamic simulator reproduces, through the use of a mathematical model, the dynamic behaviour of a physical or abstract system such as the cart in Figure 1. Such simulators provide a two-sided advantage. First, they support the concept of a dynamic universe, and second they can be included in online resources applicable to the engineering education. This will become apparent during the next sections.

When developing simulations, there are several aspects to take into consideration. One may start with defining what the learning outcome should be for students using the simulation. On the other side, it is in fact possible for one simulation to be used in learning on different levels. By removing parameters, or automating some settings, a highly advanced simulation may be used for learning more fundamental aspects of a process, even if the simulation offers the possibility to modify every single parameter inflicting the process. Also, the simulation may be used only to present a concept without emphasis on the

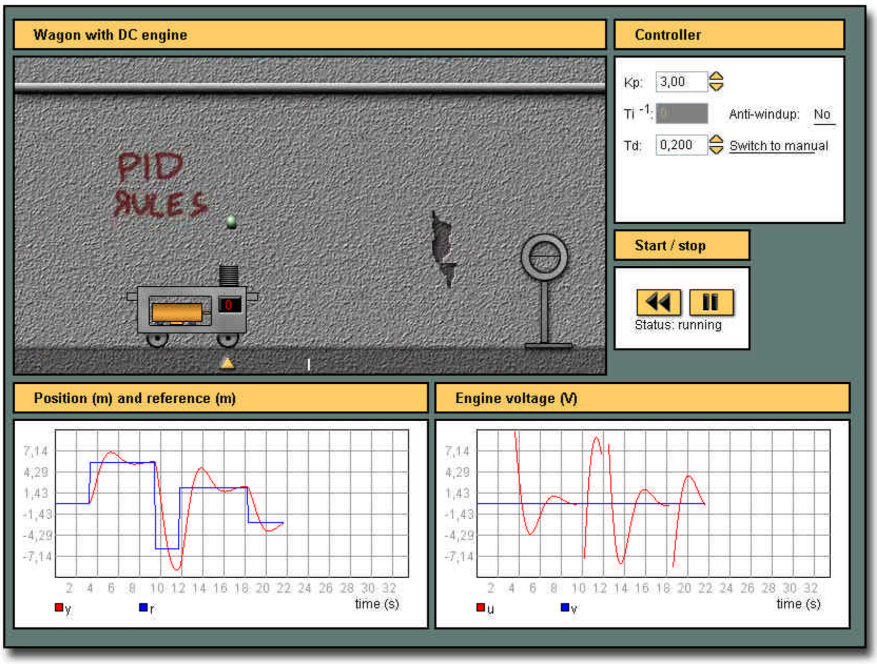

Figure 1 An educational game – controlling a cart so as to catch falling balls – is presented through multiple views.

mathematical or even some of the underlying theoretical aspects. In addition it may be possible to incorporate certain simulations in other subject matters than those they are designed for, as certain core processes are highly relevant to several adjacent subjects.

Another starting point when developing simulations may be the form of representation. One may decide to present for instance a physical mechanism, like in this case a mass-damper-spring system, in its most simple form. However, one may improve the students' possibility for grasping the concept presented by relating the simulation to real life settings — theoretically speaking, by relating it to the students' existing knowledge, allowing them to reflect and build on this.

To increase motivation, it is also possible to find a metaphor that is suited for developing the simulation into a game. To our knowledge, little research is conducted on the use of computer games in higher education teaching. Yet, earlier experiences with using the PIDstop simulation platform at the Norwegian University of Science and Technology indicate that the students appreciate the novelty and variation offered by this. The result is that they dedicate more time to exercises based on these simulations, presumably resulting in better learning.

There are a number of factors to consider when trying to turn a dynamic simulation into a game that is motivating, and at the same time maintains academical credibility and offer a realistic setting that supports the students' process of reflection and knowledge development. Also, there is a limitation on resources. Computer games are increasingly realistic, bordering on cinematic quality. Higher education institutions will never be able to compete with these games with respect to playability, or sophistication in graphics and audio. Still, it is possible to make stimulating and interesting games simulations in 2D with simple audio effects. All the youngsters who spent countless hours playing games on their ZX Spectrum and Commodore 64 machines during the 80's are proof of that, and still children are delighted by the many simple Java and Flash games available for free on the Internet.

Some important factors to develop successful simulation games are, as we see them:

- The metaphor or context chosen for the game should be easily recognizable.
- The role of the process being simulated must be obvious in the game.
- The game should comply to physical laws (which is not necessary in traditional computer games).
- The goal of the game should not be fully achievable through trial and error.
- Sound effects are not vital, but could be incorporated to prevent the game from appearing too simplistic.
- The use of humour is expected to increase motivation in students in higher education.
- There should be several levels. This will in itself give the student valuable feedback on her or his progress and increase motivation.
- Rankings, using time or points as scores, gives a competitive edge that will increase the probability that students try several times.

III. THE PIDSTOP SYSTEM

The name of the prototype system used in this paper is PIDstop. The name arises from a merger of the terms "pitstop" and "PID-control". Pitstop a place to fuel or more generally perform maintenance of a racing car, the analogy in our context is "tanking up knowledge". PID-control is an important term within the control engineering domain, the starting point of PIDstop in 2002.

PIDstop can be integrated into any modern Learning Management System (LMS). The system is implemented using HTML/CSS, powered by a PHP server for dynamic content and mySQL database for storing user data. The dynamic simulations and games are implemented as Java Applets. This means that PIDstop learning resources are available to anyone with a Java-enabled browser.

IV. Online learning resources – Some examples

During the last couple of years a number of online learning resources have been developed within the PIDstop system. We will describe a few selected learning resources for conveying knowledge on the following phenomena: harmonic oscillations, magnetic levitation, and hydrodynamic forces. [8] gives some more details on these resources and evaluation of the results.

A. Harmonic oscillators

The basis for these online resources is a dynamic simulator of a pendulum which is used both to highlight harmonic oscillations, as well as properties of an unstable system as encountered in an inverted pendulum.

The pendulum is depicted in two different wrappings in Figure 2. The student may vary the weight of the ball at the end of the pendulum, the length of the pendulum, and the initial conditions. Results may be viewed in different ways; through the animation of the pendulum itself, or through time-series plots. Further, the learning resource includes quizzes both for self-testing, and final and immediate approval of the assignment. If the student fails the final test, it must be retaken until passed. The learning resource includes standard background material on the physical system like a verbal description as well as a mathematical model.

The pendulum shows a fairly standard learning resource. In Figure 3 new elements are introduced. Emphasis is on an inverted pendulum and the simulator is wrapped into a game where the user needs to balance the feeding line in an upright position and position the cart below the helicopter so as to refuel it. The game includes well-known game features: The user has a number of “lives” available, there is a highscore list, animation, and multiple views.

B. Magnetic levitation

Magnetic levitation is an important physical phenomenon which is applicable in many situations. We show two dynamic interactive simulators in Figure 4, a ball balancing in a magnetic field and a magnetic levitation train. The underlying phenomenon is the same, the wrappings are however quite different. Both simulators allow the user to vary the current to control the vertical position of the ball or train. We claim that these learning resources can be labelled "visually pleasing". This is critically important as our later user testing will show. These simulators are an integrated part of two different learning resources which, again, are designed to motivate and maintain interest from the user through a goal-oriented learning process and the use of competitive features.

C. Hydrodynamic forces

Hydrodynamic forces are important for all sea-faring vessels. An autonomous underwater vehicle (AUV) moving in a two-dimensional universe, ie. horizontally and vertically, is the basis for the learning resource shown in Figure 5. The AUV can be steered by varying the propeller thrust and the rudder angle. This simulator can be used to study hydrodynamic forces. The movements are observed visually and recorded through time-series plots as shown to the right in the figure. This data can if needed be analysed offline. Functions described for the harmonic oscillators and magnetic levitation resources are also included.

This resource includes a particular feature: Each individual user is assigned a unique set of parameters meaning for instance that the weight of the AUV is different for each user. In the depicted simulator the task is to calculate unknown AUV-parameters, like its weight, by observing and analysing its movements. The fact that each and every student receives a unique AUV prevents students from copying answers from fellow students. The least they need to understand is copying the procedure for obtaining the answers.

D. Nonlinear control theory education

Duckmaze is a simulation game developed for a graduate course in nonlinear control theory. More details on Duckmaze can be found in [9]. An important part of this course is analysis of stability and design of controllers for nonlinear systems using Lyapunov techniques. Other important techniques are input-output linearization, backstepping and passivity theory. The intention of the applet is to give the students some tuning experiences for nonlinear controllers.

A mass-damper-spring system with nonlinear spring force is the case study, and this system has been chosen because it is a system where nonlinear control theory enables better control than the linear control theories that the students have learned in their undergraduate courses, thus creating motivation for the course in nonlinear control theory. It is also quite simple both to analyse and to visualize, and it is possible to make an attractive game

Figure 2 A pendulum shown in two different wrappings.

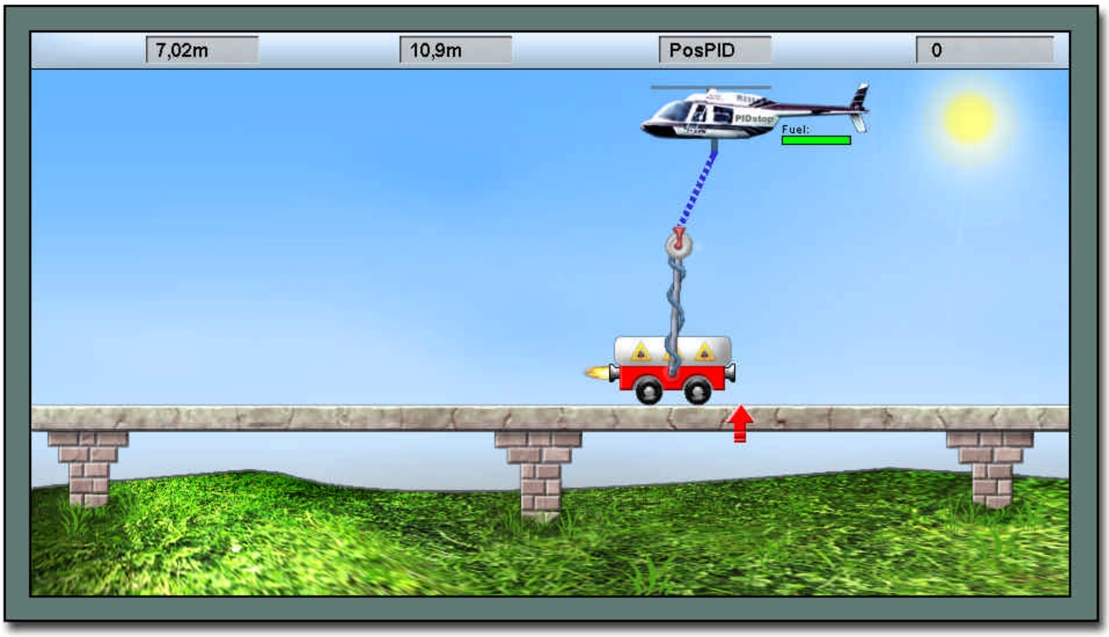

Figure 3 An inverted pendulum used in a game setting

out of it that looks like other popular 2D games, which can be found everywhere on the Internet.

The simulation game is presented to the students in the context of a mandatory exercise, which in addition to the game contains problems in nonlinear analysis and control design related to the game. The problems require the students to analyse mathematical expressions for the system and to develop nonlinear controllers using design methods from the course syllabus. This kind of problems has been given to the students for several years. The new aspect is that now they also have the ability to test the controllers on a simulator of the mass-damper-spring system. This also gives them some tuning experiences of the nonlinear controllers. Simulations from earlier courses have usually involved using simulation programs like Matlab/Simulink, which produce state plots as a function of time. In this applet an actual graphical representation of the system is given, which makes the simulation more attractive. The applet has two modes, a practice mode and a game mode where the game mode has been included to catch the students' interest.

The game mode is shown in Figure 6, and the mass-damper-spring system can be easily recognized at the bottom of the figure. This is important as explained earlier. Water has been placed on the top of it and the idea is to control the position of the duck on the water surface by controlling the position of the mass-damper-spring system. The position can either be controlled manually by using a scrollbar or by using a controller. The game scenario is as follows: A duck is very hungry and needs food really fast. It is very lucky since a blueberry muffin exists to the right of the screen. The problem is that between the duck and the muffin there are a lot of obstacles that the duck must get through. The game-player's job is to control the position of the water surface so that the duck can swim through the small openings in the maze through three skill levels.

E. Recruitment

A PIDstop-based dynamic simulation game based on a

Figure 4 Magnetic levitation is visualised in two different disguises. To the left a magnetic ball balances in an electromagnetic field. To the right a magnetic levitation train is used in an educational game.

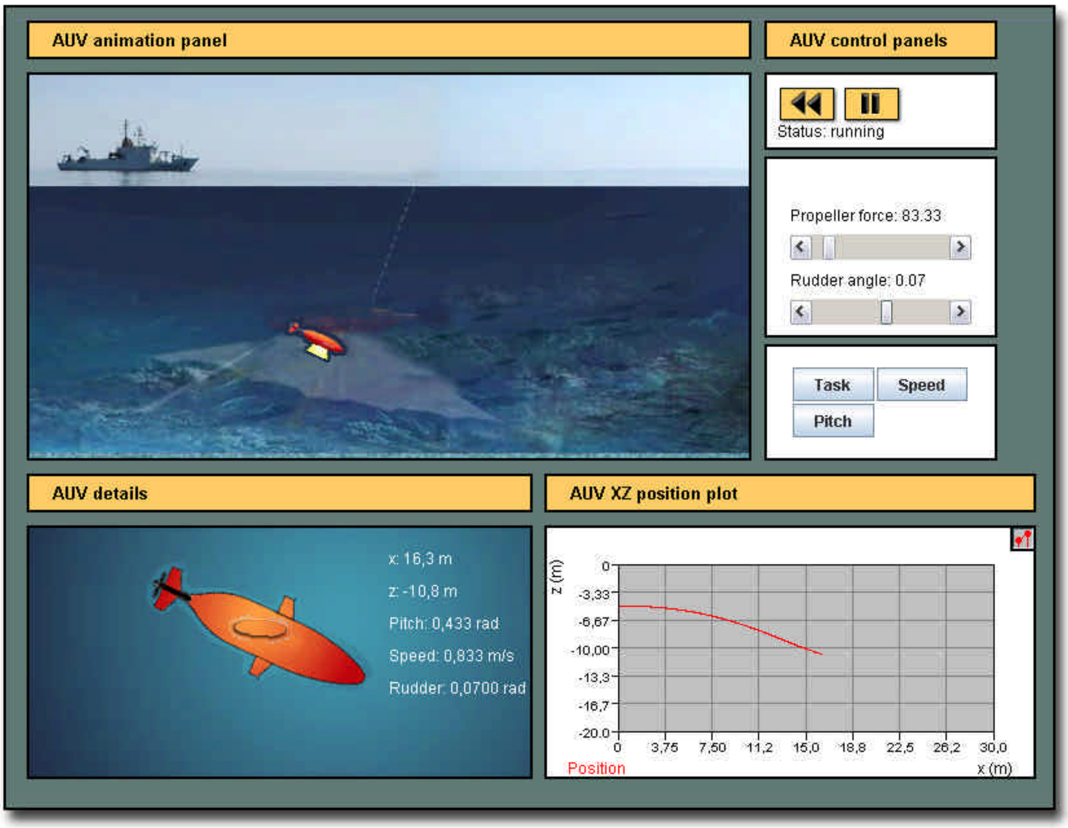

Figure 5 A learning resource utilising an autonomous underwater vehicle to convey and inspire understanding of hydrodynamic forces. The game uses multiple views.

magnetic levitation train was used for the web-based recruitment campaign for NTNU in 2005. During the three-month campaign, more than 8000 completed simulation-runs were recorded. It is not easy to measure user satisfaction at web-based campaigns like this, but the web-logs indicate that the average user played the simulation-based game approx. 5 times.

F. *Trade fairs and exhibitions*

A number of simulation-based games and competitions have been developed for industrial trade fairs and exhibitions in addition to a number of exhibitions

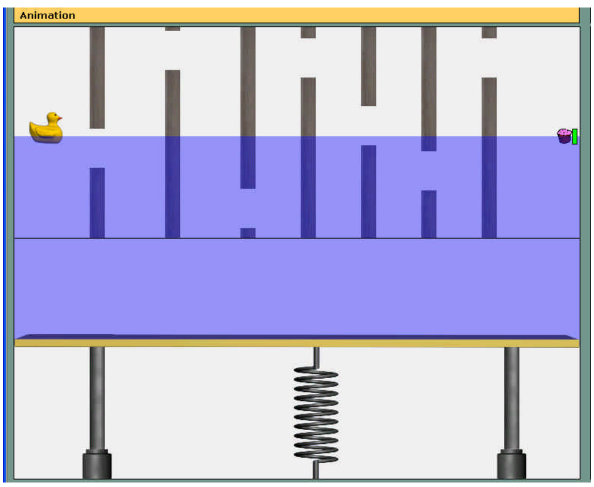

Figure 6 Duckmaze nonlinear control game

on technology dissemination towards young children (from approx. 10 years and up). The response has been very promising, even when using dynamic simulators adapted from advances usage at the university level.

G. *Vocational training*

Our results also clearly indicate that simulation-based games can be used as a helpful complement to traditional learning resources also for vocational training. This has been investigated in a national and an international project targeting vocational training of automation technicians.

V. USER EXPERIENCE

Table 1 gives an overview of the use of PIDstop in regular courses at NTNU during 2003 and 2004. The total number of users in these courses is close to 1000. External use at exhibitions, in external courses and for university recruitment campaigns is not included in the table. In the following we present in some depth the evaluation from three different courses, Calculus 1, Physics, and Control engineering during 2003 and 2004.

A. *Calculus 1*

PIDstop was used in the introductory part of the basic mathematics course for first year students. The compulsory exercise comprised one weeks work and consisted of two parts, a traditional exercise and a PIDstop assignment. The application was an inverted pendulum. The students, working in groups of three, switched between the traditional exercise and PIDstop, and the difficulty of the tasks grew throughout the week. On the

TABLE I.
THIS TABLE SUMMARIZES THE USE OF PIDSTOP IN SOME OF THE REGULAR COURSES AT NTNU DURING 2003 AND 2004.

Course – code	Department	Semester	No. of students	Level
Calculus 1 – TMA4100	Mathematical sciences	Fall 04	150	1st year
Physics – TFY4115	Physics	Fall 04	140	2nd year
Energy & environ. physics - TFY4300/FY2201	Physics	Fall 04	30	3rd / 4th year
Control introduction - TTK4100	Engineering cybernetics	Spring 04	80	1st year
Control engineering – TTK4105	Engineering cybernetics	Spring 03, 04	2 x 250	3rd year
Nonlinear control TTK4150	Engineering cybernetics	Fall 04	50	4th year

last day, the students could challenge their competence through a simulator game. The challenge was to position the tanking vehicle and its nozzle so as to re-fuel the helicopter to prevent it from crashing. Each player had three lives and a high score list was available. Feedback from 150 students from two different study programs was collected.

The students clearly favoured the combined use of traditional exercise and PIDstop to a traditional exercise by itself as observed by the very high score of 5.3 out of 6. Decomposing this finding, there is also a preference towards the PIDstop learning resource as opposed to pen-and-pencil calculations. It is also interesting to observe that the assignment clearly helped to illustrate the use of mathematics within the students' discipline. Another question was however less conclusive; The assignment did not inspire too many students to learn more mathematics (score of 3.9 out of 6). Digging deeper into the data this probably is caused by the fact that many of the students perceived the overall level of difficulty of the assignment as too high. This is probably also the main reason for the score of 3.8 on the overall impression of the assignment. The results clearly showed that the users experienced the PIDstop learning resource as user friendly and with a satisfactory functionality (score of 5.1 out of 6).

The calculus 1 assignment was repeated during fall 2005 with some minor adjustments and improvements, especially on the theoretical part. The feedback from the students showed a clear improvement from the 2004 assignment.

B. Physics

PIDstop was used in two separate compulsory exercises. The topics were the Carnot cycle, or a heat pump, and harmonic oscillations, respectively. The exercises were completed individually or in groups of two students. The harmonic oscillation assignment will be discussed in some detail. The exercise included three parts: undamped oscillation, damped oscillation and forced oscillations as eg. seen in a grandfather clock where some external force is applied to maintain the amplitude of the oscillations (Figure 2). The students were asked to perform some pen-and-pencil calculations as an integrated part of the PIDstop exercise. The feedback from 140 students was collected.

The students typically used 2 hours to complete the pen-and-pencil calculations and a little less time was spent on the simulator. This did, however, vary a lot. It is also apparent from textual feedback that the students more or less can be categorised into two groups. The first group is very enthusiastic on the use of PIDstop and claims that the use of the simulator with the additional learning resources clearly improves learning, while a second group has a neutral attitude towards the use of a simulator. These groups seem to be fairly equal in size. The first group emphasizes the importance of being able to experiment and to observe the results in different ways, in particular through animation and time-series plots.

The results clearly conveyed that the students, on an average, experienced PIDstop as having a positive learning effect. Further, and important, the students found PIDstop's user friendliness and functionality as very good. This is important since the learning effect of PIDstop will be blurred if user friendliness and functionality is not experienced as satisfactory.

C. Control engineering

A control engineering course for 3rd year students is one out of many control engineering courses where PIDstop has been used.. The results from the spring semester 2003 will be presented in some detail. The assignment was compulsory and based on the cart simulator shown in Figure 1. The assignment was divided into three with an escalating degree of difficulty. Further, there were intermediate tests as a means to qualify for a more advanced level. The exercise included a game in which the user by controlling a DC motor should catch as many falling balls as possible. This requires a well-tuned controller meaning that the students need to put control theory into practical use, at least if the ambition is to qualify for the high score list.

The exercise was used by 129 groups totalling 250 students following four different study programs. The evaluation was designed as a single page evaluation form with 20 questions and the possibility to include textual remarks. The results are much in line with the results from the assignment in the Physics course. The students also responded to the question "Do you think you learnt more or less by using this type of assignment compared to the traditional assignment?". 74% choose the category "We thought we learned more or a lot more", meaning that the students felt that this exercise was beneficial from a learning viewpoint. The results also showed that the students on average spent 3.5 hours on the exercise.

VI. Conclusions

The trial results presented in this paper are representative also for the feedback from rest of the courses listed in Table 1.

The results clearly substantiate the hypothesis that educational games provide a useful concept for online learning resources within the engineering domain. There are several reasons for this. First, there is a spread in the students' background ranging from 1st year to 4th year students. Second, the educational games are tested on students from four different engineering study programs. Finally, the total number of students is quite large. Hence, the breadth in the trials is substantial.

A finding from our trials is that students may coarsely be divided into two groups. One group claims that the use of the simulator with the additional learning resources provided by PIDstop clearly improves their learning, while a second group has a neutral attitude towards the use of these educational games. These groups seem to be fairly equal in size. The first group emphasizes the importance of being able to experiment on a dynamic simulator and to observe the results in different ways, in particular through animation and time-series plots, and that this interactive universe is important for their learning experience. Further, these users clearly favoured the combined use of a traditional exercise with a highly interactive learning arena like PIDstop as opposed to a traditional exercise by itself. Finally, the users are stimulated by the immediate feedback through intermediate tests.

A limitation of the study is the fact that engineering education only, is targeted in this work. This implies that the findings are, to some extent, limited. On the other hand engineering education is a large and important sector in higher education. Furthermore, the results are positive. Hence, they should at least show promise also for other sectors in higher educations.

A second limitation of the study is the fact that feedback is based on the perceived learning experience by the students. There has been no comparative study on for instance the final grades of students using PIDstop compared to the study not exposed to these learning resources. We will, however, claim that a positive learning experience, as reported in the feedback from the majority of students using PIDstop, is a necessary requirement for improved learning.

Today's computer games have very high standards when it comes to functionality, user friendliness and graphics. This is a challenge since the user of educational games will compare these to other computer games. Hence, to provide a fair comparison it is, in our experience, critically important to design learning resources which are visually pleasing and with good functionality. If this is not satisfied students will be distracted in their learning process by issues like low quality graphics making it exceedingly difficult to test the effect of eductional games. It should be mentioned that it has been a major effort to develop PIDstop to satisfy these criteria. User feedback summarized in this paper and in [8], shows that this has been successful.

To sum up, we conclude that dynamical simulators shaped as educational games, in the context of this study, has a positive learning effect on a substantial part of typical students in engineering programs.

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