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Effectiveness of Animation as a Learning Strategy in a Classical Control Theory Introductory Course

Darío A. Weitz*

Facultad Regional Rosario, Universidad Tecnológica Nacional, Rosario (2000), Argentina
*Corresponding author: dar.wtz@gmail.com

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Abstract Classical Control Theory (CCT) is one of the general education courses for many university engineering curricula. Course contents usually have deep theoretical definitions, high level of abstraction, computationally intensive procedures and demand students with a solid mathematical background. In the present paper, we explore how animation has the potential to contribute to the learning and comprehension of several contents included in a CCT introductory course. Based on current theories of multimedia learning, we incorporated animation components in modules designed for teaching various educational contents. Animation is an efficient didactic tool for explaining theoretical definitions, underlying methodologies involved in diagrams construction and computational procedures described on a CCT introductory course. We recommend that animation should be included in every CCT educational software.

Keywords: *control theory, control education, educational software, animation*

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1. Introduction

Classical Control Theory (CCT) is one of the general education courses for many university engineering curricula. CCT is included as a subject in Systems Engineering, Process Engineering, Electronics, Electrical, Industrial and other "non-traditional" engineering careers that appeared in last decades. Course contents usually have deep theoretical definitions, computationally intensive procedures, high level of abstraction and demand students with a solid mathematical background. Students often perceive control theory basic contents as a “large collection of abstract math” [1].

Time for development of contents is usually limited to one semester long, which is a challenge for teachers of these courses, as occurs in Ingeniería en Sistemas de Información at the Universidad Tecnológica Nacional in Argentina. Therefore, professors must do a significant pruning in a field of knowledge that has grown dramatically in the last sixty years. A further restriction is that some theoretical definitions, computational methods, and analysis and design tools must be teached without losing sight that they will evolve during the future engineer working life. As a result, it is desirable that teachers of CCT courses make use of new didactic tools to overcome those restrictions.

Methods, procedures, and diagrams taught in an introductory course in Control Theory have been developed in powerful high-level languages such as MATLAB, Mathematica and Scilab. However, they exhibit significant limitations at the time the instructor, at the very beginning of the course, attempts to explain the basic concepts and the underlying methodologies involved in diagrams construction and computational procedures. From a pedagogical point of view, they should be used to complement the teaching task once students have incorporated the initial contents of the subject.

Applications of control are growing rapidly in several engineering fields accompanied by a wider non-technical audience using control systems in a daily basis. Correspondingly, there is a need to develop new educational approaches to improve learning for technical users and accessibility by new non-traditional audiences. In this sense, the Panel on Future Directions in Control, Dynamics and Systems suggests: “Encourage the development of new courses and course materials that will significantly broaden the standard first introductory control course at the undergraduate level” [2].

Computers have provided new possibilities and strategies for innovative learning environments. Computer-based instruction, educational multimedia systems and animated graphics are frequently employed for teaching complex systems and abstract concepts. In the present paper, we explore how animation has the potential to contribute to the learning and comprehension of several contents included in a CCT introductory course. Modules of an educational software which integrates animation as part of its learning strategy are described.

2. Animation and Cognitive Process

Animation is described as a pictorial display that changes its structure or other properties over time and which triggers the perception of a continuous change [3]. In educational environments, animations are often used to improve students' understanding of certain complex processes or abstract concepts that change over time and space. Animation has been employed in teaching complex systems such as mechanical, biological, physical, operational and computational. Animations has been used in natural sciences such as physics, chemistry, biology, etc., to visualize scientific concepts and their relationships through abstract graphical representations. It has also been used in software instruction for better understanding of algorithms and data structures [4].

Several studies examined the effectiveness of animation as a learning strategy against equivalent static graphics. Results were contradictory: a meta-analysis [5] shows that animation has significant advantages compared with learning from static pictures, while Tversky et al. [6] shows some failures to find benefits of animation compared with equivalent static diagrams. Even in successful cases, it has been observed that animation entails very specific demands in students' learning process: they must understand continuously changing information and identify and relate elements that are taking different spatial locations over time. As a result, some students are overwhelmed by the intensity of the information they are receiving and not able to systematically process the material presented to them. Therefore, it is advisable to use current theories of multimedia learning to assess a priori whether the subjects and contents of the course are suitable for using animation as a didactic tool.

The cognitive theory of multimedia learning is one of the most comprehensive theories dealing with multimedia based learning in general and instructional animations in particular [7]. The basic assumption of this theory is the dual coding hypothesis. It assumes that information is processed through two separate but interconnected channels: a channel processing verbal information and another channel processing visual information. When knowledge is encoded in both verbal and non-verbal modes, learners are allowed to build dual representations in their brains and to make referential connections between those representations [8]. As a result, transfer of knowledge occurs in an efficient and robust way compared with any other technique that does not involve dual coding.

Another learning theory related with animation is epistemic fidelity. It focuses attention on the fidelity of an external display with respect to an expert's mental model. The theory assumes that transfer of knowledge can be improved when the external representation describes the expert mental model as closely as possible. If the external representation portrays the expert's mental model with high fidelity and clarity, and with less ambiguity, the viewer of the visualization decodes and internalizes knowledge in a robust and efficient way [8].

Other studies [6] have shown that graphics, and particularly animations, can facilitate comprehension and learning only if they are appropriate and carefully designed. In this sense, visualizations must conform both to the Congruence Principle and the Apprehension Principle.

The Congruence Principle states that for an effective graphic representation, the structure and content of the external representation should be consistent with the desired structure and content of the internal representation. Content and format of the images should correspond with content and format of the concepts presented. Accordingly, animation should be particularly helpful when contents or structures include changes over time, abstract processes or metaphoric change.

An animation strategy may be inefficient if the instructional graphics violate the Apprehension Principle. It states that structure and content of the external representation should be readily and accurately perceived and comprehended. Perception or comprehension is hampered when images move too fast or are very complex to understand.

Weiss et al. [9] present a set of practical heuristics for using animation in educational software. They analyzed the specific nature of animation by describing its characteristics and purposes. Related with the inherent purposes of animation, they suggest the following five functions of the technique: cosmetic; attention gaining; motivation; presentation; and clarification function. They analyzed the physical nature of animation through surface structure (texture, color) and fidelity level. They distinguish between physical fidelity –how closely the animation resembles the real world– and functional fidelity –how closely the animation behaves as the object or process of the real world–.

Movement and trajectory are inherent characteristics in an animation. According to Weiss et al. [9], there is no reason to use animation as a didactic tool if those elements are not present on the subject matters of the course. If movement and trajectory are present on the subject matter, animation can be used for presentation or clarification of contents. Animation as a presentation function includes giving a visual context to ideas, codify information in the dual code way and to provide examples of dynamic systems or highly abstract processes. Animation as a clarification function involves the understanding of a new concept or a new relationship without providing additional textual information.

If learning general objectives and basic contents are conducive to the use of animation, fidelity level and surface structure must be analyzed previous to software design. Usually, they may be different depending if learning contents are concepts or procedures. Animation is particularly useful for teaching relatively abstract and complex concepts which involve changes over time, systems affected by simultaneous influences or the sensitivity of a process to changes in a particular variable. In a system affected by simultaneous influences, animation helps to overcome our natural tendency to process information sequentially. According to Rieber and Kini [10], animation should be present when "changes over time" and "directional characteristics", difficult to describe verbally, are included in the concepts or procedures to be taught. For concepts, surface structure and fidelity level should be adjusted to the needs and abilities of the students. For procedures, surface structure and fidelity level must be high, so the instructional animation is the best possible representation of the actual procedure.

3. Animation in a CCT Educational Software

The educational software consists of several modules corresponding to various instructional contents: physical examples of first and second order systems; transient response to a step input; response to a sinusoidal input; location of the roots and impulse response; response of first and second order systems to a ramp input; Root Locus method; Bode Plots; Nyquist Diagrams; tuning of PID controllers [11,12,13]. Weitz [14] describes the employment of the software for a faster and comprehensive teaching of the basic objectives in feedback control systems analysis and design. The software also allows with relative ease the explanation of rules, computational procedures and conclusions involved in Root Locus, Bode Plots and Nyquist Diagrams.

3.1. Physical Examples Module

The module Physical examples of first and second order systems provides examples of dynamic systems such as a mercury thermometer, a one tank liquid-level system and a two-tank noninteracting liquid-level system (Figure 1). Also includes the trajectories of an airplane and a submarine after a step input. In all of them, the idea is to represent the behavior of the physical system (physical fidelity), but also the animated graphic of the time response together with a numerical indication of the present value of the response variable (functional fidelity). By way of anticipation the concepts of modern control theory, a two-tank interacting liquid-level system animation is simultaneously presented. In the same module, there is an instructional animation of a feedback loop: the visualization shows the simultaneous change over time of several variables presented in the loop (set point, error, control signal, actuator signal, response variable). The objective of this animation is to capture the essence of feedback as a situation in which two or more dynamical systems are connected together such that each system influences the other and their dynamics are thus strongly coupled [15]. It is an example of a system affected by simultaneous influences, where animation helps the students to overcome the counterintuitive behavior of feedback systems.

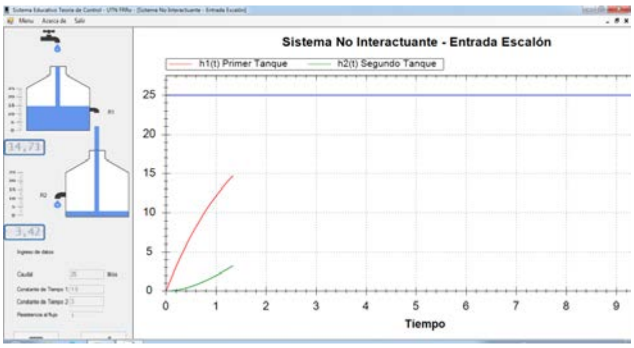

Figure 1. Animation of a two-tank noninteracting liquid-level system

3.2. Root Locus Module

The Root Locus module was designed for an efficient teaching of the rules introduced by Evans for plotting root locus diagrams of characteristic equations of any order. The following animation elements were incorporated in the module: i) after choosing the plant dynamics and a mode of control, and clicking on a check box named "Pasos Automáticos" (Automatic Steps), all the steps needed to plot the root locus are automatically and successively described on the screen, coupled with the consequent changes in the diagram. The instructor accompanies the changes in the diagram with appropriate verbal explanations, as suggested by the dual coding hypothesis; ii) once the drawing is concluded, it is possible to click on the icon named "Regla Anterior" (Previous Rule) in order to move back in the description of the rules and in the drawing of the diagram. This possibility of moving back to review methodological aspects is an efficient way for improving the comprehension of the rules; iii) the directional characteristics of the root locus is enhanced by an animation showing the trajectory of the locus from its origin at poles till its end at zeros or at infinity along the asymptotes (Figure 2). The animation speed was chosen taking into account the Apprehension Principle.

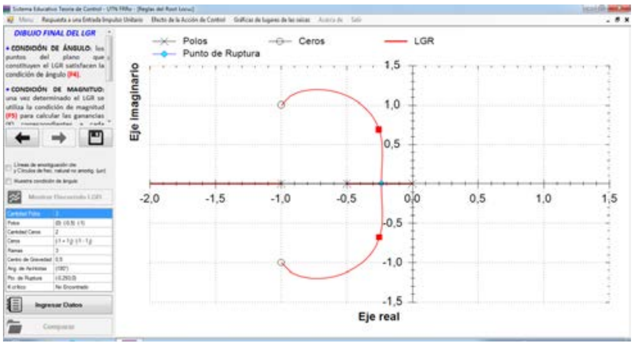

Figure 2. Animation showing directional characteristics of the root locus method

3.3. Bode Plots Module

The Bode Plots module was designed to show how the overall curve is constructed by successive adding of the individual components of the transfer function. The following animation characteristics were incorporated in the module: i) after choosing the plant dynamics and a mode of control, and clicking on a check box named "Pasos Automáticos" (Automatic Steps), the individual components are automatically and successively drawn on the screen in different colors accordingly to their corner frequencies. The (partial) overall curve is simultaneously drawn, so the animation, acting as a clarification function, enables an efficient comprehension of the graphical rules employed in Bode plots; ii) once the drawing is concluded, it is possible to click on the icon named "Retroceder" (Move Back) in order to go back in the drawing proce-dure to review its methodological aspects; iii) the individual component whose layout is being drawn is highlighted in the overall transfer function in order to clarify its contribution to the overall curve. The animation speed was chosen taking into account the Apprehension Principle.

3.4. Nyquist Diagrams Module

The Nyquist Diagrams module was designed, according to Cheever [16], to show the mapping of functions following the Nyquist path in the complex plane. The following animation characteristics were incorporated in the module: i) the mapping of functions with a single zero, a single pole, multiple poles and zeros, and functions following the Nyquist path are drawn with a pointing arrow and nine changes of colors to show the trajectory described by the original function and the mapped one (Figure 3). Here we use the animation as a presentation function, so to give a visual context to an abstract mathematical technique; ii) during the mapping, dotted lines link the poles with the Nyquist path in the first diagram and the origin with the Nyquist curve in the second diagram. Here the animation is employed as a presentation function of the subtended angles and the difference in magnitude between the original and the mapped function. The animation speed was chosen taking into account the Apprehension Principle.

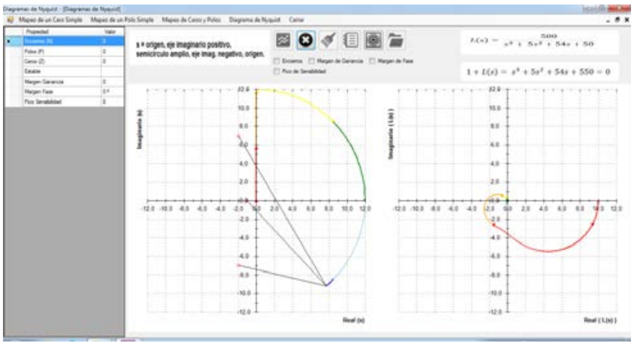

Figure 3. Animation of the trajectories in a Nyquist Diagram

3.5. PID Tuning Module

The PID tuning module was designed to explain several procedures employed for setting control parameters for a PID controller. The following animation characteristics were incorporated in the module: i) in the open loop test based on a first order plus dead time model (Ziegler – Nichols, Cohen – Coon, etc.), learners receive the following sequence: first, the gain horizontal line is drawn, then the S-shape response curve, then the tangent line to the response curve, and finally the horizontal lines corresponding to delay and time constant (Figure 4). Once the drawing is completed, the tables with controller settings are shown at the screen. The animation sequence, designed with a high functional fidelity level, acts as a presentation function of the procedures used to calculate the controller values based on the open loop test. The animation speed was chosen taking into account the Apprehension Principle; ii) in the closed loop test (Ziegler – Nichols ultimate gain) the screen "is broken" en three parts to show animated response curves for increasing values of the controller gain. The third curve corresponds to the proportional-only gain that causes the control loop to oscillate indefinitely. Here we use the animation based on the dual coding hypothesis: while the professor describes the procedure verbally, the animation sends visual information so learners are allowed to build dual representations and make referential connections between them.

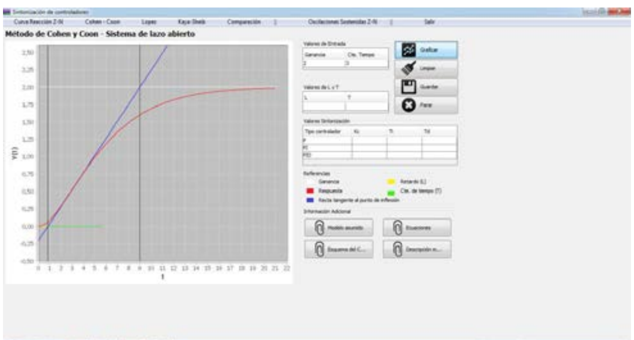

Figure 4. Animation of the Cohen-Coon open loop test

4. Results

The educational software was developed using Microsoft Visual C# and Java. Zedgraph was employed for graphics and drawings. User interface is friendly and intuitive. Most of the data entered is numeric, validated with regard to data type and value range. All curves are plotted in different colors and have their corresponding legend for proper identification. Software was designed according to Congruence Principle and the Apprehension Principle.

Animation is justified because movement and trajectory are present in course contents. In a first stage, animation acts as a presentation strategy, to give a visual context of a complex, difficult idea to be orally introduced. Thereafter, acting as a clarification function it improves understanding of new concepts or new methods with little additional textual information. Realism and fidelity levels were adjusted to the needs and abilities of the learners.

The educational software was employed in three courses during the first semesters of 2013 and 2014. At the end of the 2014 semester, a perception survey of the software usefulness was completed by the students. The survey (79 students) showed the following results:

- 96% of the students considered important the use of the educational software as a didactic tool.
- The survey showed that students comprehended better contents that included animation (Root Locus, Bode Plots, PID tuning) compared with another modules of the educational software (sinusoidal response of first and second order systems, impulse response, stability analysis).
- Related with the inherent purposes of animation, 89% of survey respondents answered that it was useful for clarification of methods and concepts. Being a multiple response question, it was found that the software was also useful for presentation of new concepts (40%) and for attention gaining (57%).
- Students were asked to rate on a 1 to 5 scale the software benefits in the understanding of the methods. The LGR method got an average score of 4.30, while Bode Plots got 4.05 and Nyquist Diagams 4.35.
- Graphic quality, explanatory texts, input and results tables and checkboxes were evaluated. The survey showed the need to enhance several explanatory texts, both in font size and color contrast. There were also several suggestions regarding improvements to input and results tables.
- 54% of survey respondents were able to identify at least three elements of animation in the software.

A small group of students, that failed the exams during previous years, were able to compare learning from static pictures versus the animation technique. They concluded that concepts and methods were easily understood with the new approach. They assured that understanding from animations was significantly more successful than learning from static graphical representations.

Final exams success rates during previous years (2011 – 2012) were 77.3% y 73.5% respectively. After using the educational software, percentage rates increased to 81.3 in 2013 y 84.6 during the 2014 academic year.

5. Conclusions

Classical control theory is considered a well established engineering science discipline with clear objectives and powerful methods and procedures for analysis and design. Most university engineering curricula have a CCT course as a required one, and most face similar troubles: engineering students struggle to understand abstract theoretical definitions, computationally intensive methods and procedures included in course contents.

Traditional engineering education employs static pictures for teaching students. Based on current theories of multimedia learning (cognitive theory of multimedia learning, epistemic fidelity), principles for successful animated graphics (Congruence Principle, Apprehension Principle) and practical heuristics, we incorporated animation elements in modules designed for teaching various educational contents habitually included in a CCT course. We used animated graphics, animated procedures, arrows, highlighting and other devices to facilitate the teaching of complex methods and abstract concepts that change in time and space.

Based on an formal survey, we claim that students appeared to come away with a better understanding of the course contents and they felt more engaged than previous groups of learners. We conclude that animation is an efficient didactic tool for explaining theoretical definitions, underlying methodologies involved in diagrams construction and computational procedures described on a CCT introductory course. Animation enhanced students' understanding of the basic objectives in feedback control systems analysis and design, and facilitated the teaching of methods used to determine the stability of feedback control systems. We recommend that animation should be included in every CCT educational software.

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