DIDACTIC SIMULATION OF A SELF-STABILIZING SYSTEM: A PEDAGOGICAL APPROACH TO TEACHING EMBEDDED SYSTEMS

SIMULAÇÃO DIDÁTICA DE UM SISTEMA AUTOESTABILIZADOR: UMA ABORDAGEM PEDAGÓGICA PARA O ENSINO DE SISTEMAS EMBARCADOS

SIMULACIÓN DIDÁCTICA DE UN SISTEMA AUTOESTABILIZADOR: UN ENFOQUE PEDAGÓGICO PARA LA ENSEÑANZA DE SISTEMAS EMBEBIDOS

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ABSTRACT

This work presents a proposal for a didactic simulation of a two-dimensional self-stabilizing system, inspired by the conceptual operation of a 2D gimbal, developed on the Raspberry Pi Pico W platform. The main motivation is to provide an accessible pedagogical resource for teaching embedded systems, prioritizing the conceptual understanding of execution flow, data acquisition, processing, and feedback, without the inherent complexity of real mechanical systems. The simulation employs controlled inputs and visual and auditory outputs to represent the dynamic behavior of the system, allowing students to immediately observe the relationship between stimuli and responses. The proposal is intended for technical and undergraduate courses, as well as teacher education, standing out as an intermediate stage between theoretical study and more advanced physical projects.

Keywords: Embedded Systems. Didactic Simulation. 2D Gimbal. Technological Education. Raspberry Pi Pico W.

RESUMO

Este trabalho apresenta uma proposta de simulação didática de um sistema autoestabilizador bidimensional, inspirada no funcionamento conceitual de um gimbal 2D, desenvolvida sobre a plataforma Raspberry Pi Pico W. A motivação central é oferecer um recurso pedagógico acessível para o ensino de sistemas embarcados, priorizando a compreensão conceitual de fluxo de execução, aquisição de dados, processamento e realimentação, sem a complexidade inerente a sistemas mecânicos reais. A simulação utiliza entradas controladas e saídas visuais e sonoras para representar o comportamento dinâmico do sistema, permitindo que estudantes observem, de forma imediata, a relação entre estímulos e respostas. A proposta é voltada a cursos técnicos, de graduação e à formação de professores, destacando-se como uma etapa intermediária entre o estudo teórico e projetos físicos mais avançados.

Palavras-chave: Sistemas Embarcados. Simulação Didática. Gimbal 2D. Educação Tecnológica. Raspberry Pi Pico W.

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RESUMEN

Este trabajo presenta una propuesta de simulación didáctica de un sistema autoestabilizador bidimensional, inspirada en el funcionamiento conceptual de un gimbal 2D, desarrollada sobre la plataforma Raspberry Pi Pico W. La motivación central es ofrecer un recurso pedagógico accesible para la enseñanza de sistemas embebidos, priorizando la comprensión conceptual del flujo de ejecución, la adquisición de datos, el procesamiento y la realimentación, sin la complejidad inherente a los sistemas mecánicos reales. La simulación utiliza entradas controladas y salidas visuales y sonoras para representar el comportamiento dinámico del sistema, permitiendo que los estudiantes observen de forma inmediata la relación entre estímulos y respuestas. La propuesta está dirigida a cursos técnicos, de grado y a la formación docente, destacándose como una etapa intermedia entre el estudio teórico y proyectos físicos más avanzados.

Palabras clave: Sistemas Embebidos. Simulación Didáctica. Gimbal 2D. Educación Tecnológica. Raspberry Pi Pico W.

1 INTRODUCTION

Teaching embedded systems involves the simultaneous articulation of hardware, software, and, in many cases, physical modeling concepts. For students at early levels of education, this overlapping knowledge can lead to learning disabilities, especially when coupled with complex mechanical devices and real sensors. In this scenario, simulation-based didactic approaches have been shown to be effective in reducing the initial cognitive load, allowing the student to focus his attention on the fundamental principles of the system's functioning.

This article presents a didactic simulation of a two-dimensional self-stabilizing system, inspired by the concept of a 2D gimbal, implemented on the Raspberry Pi Pico W platform. Unlike projects aimed at real physical stabilization, the proposal has an essentially pedagogical character, seeking to represent in an abstract and visual way the dynamic behavior of the system and the role played by the embedded software.

The use of computer simulations has been consolidated as a relevant pedagogical strategy, especially in the teaching of abstract or difficult-to-visualize concepts, as discussed by Valente (2014) in the context of the use of digital technologies in education.

The work was developed with a focus on educational applications, and can be used in lectures, laboratory activities or introductory projects. The main contribution lies in the transformation of a complex technical problem into an accessible learning object, favoring the progressive understanding of the concepts involved.

2 THEORETICAL BASIS

2.1 EMBEDDED SYSTEMS IN THE EDUCATIONAL CONTEXT

Embedded systems are characterized by the integration of hardware and software dedicated to the execution of specific functions. In the educational context, low-cost and easy-to-program platforms have expanded access to this type of technology, allowing its use in technical and undergraduate courses. However, the direct introduction of complete physical systems can hinder initial learning, since it requires the student to simultaneously understand multiple layers of the system.

The use of didactic simulations emerges as a strategy to mitigate this problem, by allowing the abstraction of less relevant elements at first and highlighting the logical flow of the system's operation.

2.2 SELF-STABILIZING SYSTEMS AND GIMBALS

Self-stabilizing systems are widely used in applications such as camera stabilization, drones, and mobile platforms. A two-dimensional gimbal is a typical example, composed of two orthogonal axes that allow control of the angular orientation of an object.

In real-world applications, this control involves inertial sensors, actuators, and control algorithms. In the proposal presented in this work, these elements are represented in a conceptual way, through a computer simulation that reproduces the expected behavior of the system, without the physical implementation of the components.

Figure 1 shows the slopes in a three-dimensional system, which a self-stabilizing system has the function of reducing them to zero.

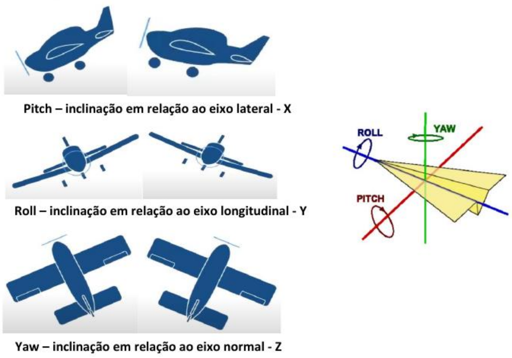
2.3 SIMULATION AS A DIDACTIC RESOURCE

From a pedagogical point of view, simulation allows the student to explore varied scenarios, observe system responses, and establish cause-and-effect relationships. This type of approach favors active learning and the gradual construction of knowledge, serving as a bridge between theory and experimental practice.

The approach adopted in this work prioritizes the conceptual understanding of the phenomenon studied, aligning itself with the perspective of meaningful learning proposed by Ausubel (1968), where new knowledge is integrated into the learner's previous cognitive structure.

Figure 1

The slopes with respect to the X, Y, and Z axes are often referred to as Pitch, Roll, and Yaw, respectively



Source: The Author (2026).

3 DIDACTIC METHODOLOGY OF SIMULATION

3.1 PRINCIPLES OF THE PROPOSED SIMULATION

The simulation was designed to represent, in an abstract way, the operation of a self-stabilizing system. Real physical sensors are replaced by controlled inputs, while actuators are represented by visual and audible outputs. This choice allows isolating the role of embedded software, highlighting processing and decision logic.

The interaction with the system occurs through well-defined events, which simulate the acquisition of data and the activation of the stabilization process. In this way, the student can understand how embedded systems operate in a cyclical and reactive manner.

The use of visual and interactive resources favors student engagement and expands the possibilities of pedagogical mediation, as argued by Moran (2007) when dealing with the integration between technology and education.

The behavior of the simulated system is based on classical control principles, widely discussed in the control engineering literature (OGATA, 2010), but presented here in an abstract and didactically accessible way.

3.2 FUNCTIONAL ARCHITECTURE OF THE SYSTEM

From a didactic point of view, the architecture of the system can be understood in three main blocks:

- **Simulated data input:** responsible for providing values that represent slopes or disturbances of the system.
- **Logical processing:** a step in which data is interpreted and used to update the state of the system, simulating the action of a stabilization algorithm.
- **Didactic outputs:** responsible for presenting the current state of the system to the user, through visual and sound resources.

This organization in blocks facilitates the understanding of the separation of responsibilities typical of embedded systems.

3.3 EXECUTION FLOW

The operation of the simulation can be understood from a conceptual flow of states, which represents the typical execution cycle of an embedded system. This flow can be presented didactically through a flowchart, making it easier to visualize the steps involved.

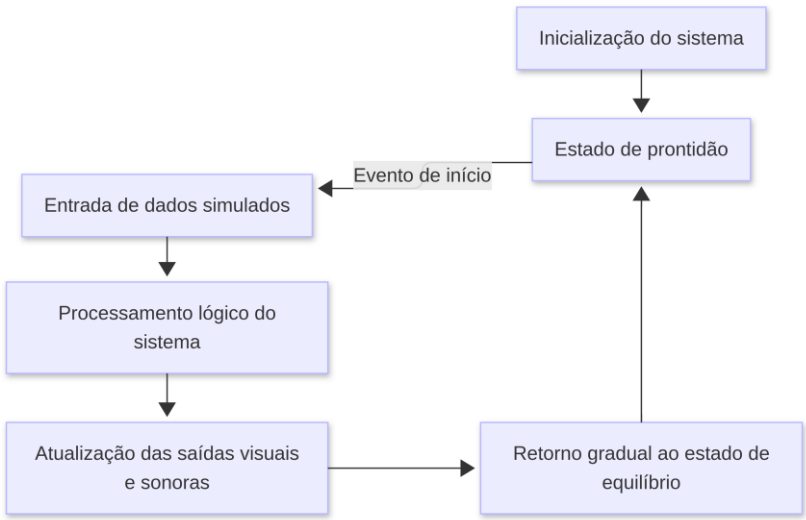
In an abstract way, the conceptual flowchart of the system can be described as follows:

1. **System Startup:** The microcontroller is energized and configures its basic capabilities, entering an initial standby state.

2. **State of readiness:** The system remains waiting for an external event that authorizes the start of the simulation, representing the logic of reactive systems.
3. **Simulated data input:** after authorization, data representing system disturbances or inclinations is provided, replacing real physical sensors.
4. **Logical processing:** the input data is interpreted and used to update the internal state of the system, simulating the behavior of a stabilization algorithm.
5. **Update of didactic outputs:** the new state of the system is presented to the user through visual and sound resources, allowing immediate observation of the response.
6. **Return to equilibrium:** the system makes a gradual transition to a reference state, reinforcing the concept of stabilization.
7. **Cycle replay:** The flow returns to the state of readiness, characterizing the main execution loop typical of embedded systems.

Figure 2

Conceptual Flowchart



Source: The Author (2026).

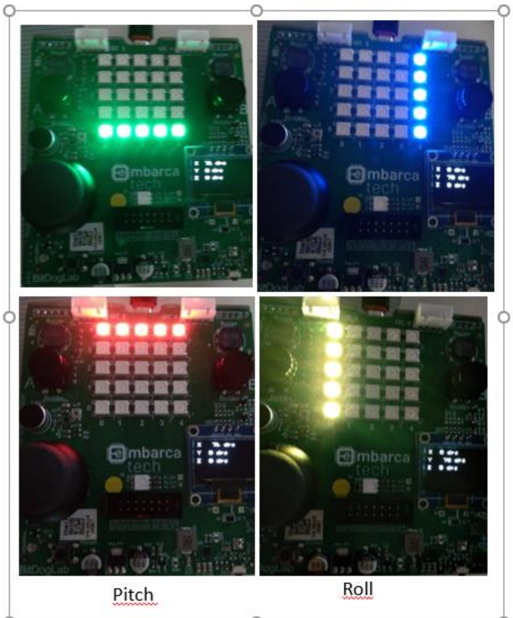
Figure 3 shows the LED array used in the simulation, in which the inclinations in the X and Y axes are represented by means of color coding. Pitch slopes are indicated by the colors green (negative pitch) and red (positive pitch), while *roll* slopes are represented by the colors blue (negative roll, slope to the left) and yellow (positive roll, slope to the right). Color combinations are used to indicate simultaneous tilts in the two axes, such as the overlapping of the blue and red colors, which results in the color purple.

The intensity of the slope is represented by the number of LEDs lit, so steeper slopes correspond to a greater number of illuminated elements in the matrix.

In the example in Figure 3, a soft Roll to the right lights up a single row of yellow LEDs and to the left lights up the blue ones. A soft downward pitch lights up a row of green LEDs and upwards lights up the red ones. On the lower left side of the matrix is an OLED display with the values of X, Y (and Z), which are continuously updated according to the action of self-stabilization.

Figure 3

The array of LEDs simulating the X and Y inclinations



Source: The Author (2026).

In Appendix A, there is a link to the GitHub page, which contains the software developed for the simulation, as well as an explanatory video.

4 RESULTS AND DISCUSSION

The use of simulation in educational contexts demonstrates potential to facilitate the understanding of the fundamental concepts of embedded systems. The immediate visualization of the system's responses to the inputs provided contributes to the association between theory and practice, as well as increasing student engagement.

By abstracting the mechanical and electronic complexity of a real system, the proposal reduces initial frustration and allows the focus to be directed to the operating logic and the role of the software.

5 EDUCATIONAL APPLICATIONS

Simulation can be used in different educational contexts, such as introductory courses on embedded systems, technical courses in automation and teacher training activities. In addition, it can serve as the basis for more advanced projects, in which actual physical components are gradually incorporated.

6 LIMITATIONS AND FUTURE WORK

As it is a didactic simulation, the proposal does not include advanced control algorithms or the detailed physical modeling of a real gimbal. These limitations are intentional and coherent with the pedagogical objective of the work. As future works, it is suggested to expand the simulation to include new modes of operation and integration with real physical systems.

7 FINAL CONSIDERATIONS

This work presented a didactic simulation of a two-dimensional self-stabilizing system, developed with a focus on the teaching of embedded systems. The proposed approach favors the conceptual understanding and visualization of the system's behavior, offering an accessible and low-cost alternative for educational environments. The results indicate that simulation can act as an effective tool in the teaching-learning process, serving as a link between theory and practice.

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APPENDIX

Link to the GitHub page containing the software developed for the simulation presented in this work, as well as a video demonstrating the simulation: https://github.com/antoniolouro/gimbals_final