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Development of a Control Systems Training Module for Application on Undergraduate Engineering Classes

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Abstract: Student access to laboratory experiments is critical in undergraduate engineering courses since it integrates theory and practice. The access of students to such practical examples helps them to understand and apply what is learned. However, due to rapid technological advancement, educational kits can quickly become obsolete. Besides, there are many known commercial platforms for training. Many of them have steep prices, which makes their availability difficult for every student. The present work proposes a low-cost ATMEGA-based system as the main device for an educational tool for training Control System Theory. The system enables the students to test different control strategies through the use of a simple educational kit.

Resumo: O acesso do aluno a experimentos de laboratório é fundamental nos cursos de graduação em engenharia, devido ao fato de ser usado para integrar teoria e prática. O acesso dos alunos a exemplos práticos os ajuda a entender e aplicar o que é aprendido. No entanto, devido ao rápido avanço tecnológico, os kits educacionais podem rapidamente se tornar obsoletos. Além disso, existem muitas plataformas comerciais conhecidas para treinamento com preços exorbitantes, o que dificulta sua disponibilidade para todos os alunos. O presente trabalho propõe um sistema ATMEGA de baixo custo como principal dispositivo para uma ferramenta educacional para o treinamento da Teoria dos Sistemas de Controle. O sistema permite que os alunos testem diferentes estratégias de controle através do uso de um kit educacional simples.

Keywords: Educational Kit, Engineering Education, Control Theory, Low-Cost Device

Palavras-chaves: Kit Educacional, Educação em Engenharia, Teoria de Controle, Dispositivo de Baixo Custo

1. INTRODUCTION

Student access to laboratory experiments is critical in undergraduate engineering courses because it is used to integrate the theory methodology development and to understand the problem Hoffenson et al. (2019). Besides, the laboratory activities are synchronized with lectures to maximize their derivable learning outcomes Achumba et al. (2013). Thus, having access to such practical examples helps students understand and apply what is learned during classes, as can be seen in Shafai and Kordi (2012) and Chołodowicz and Orłowski (2017). The difficulty of absorbing the rapid systems and equipment technological evolution is a problem in engineering education Devadiga (2017). Due to rapid technological advancement, educational kits can quickly become obsolete, making them disposable. Another issue in engineering courses is the highest dropout rate. Therefore, these educational modules should stimulate the student's development Coşkun et al. (2019).

According to work in Davies (2008), the use of teaching modules in practical disciplines has benefits concerning the exclusive use of computer simulation. As an advantage, it is possible to mention a better understanding of physical phenomena and the development of the student's skills in operating electrical equipment, as presented in Reck and Sreenivas (2016). Within this context, the use of technologies that allow student interaction with these systems is increasingly used. The development of educational kits allows adding necessary characteristics to a dynamic learning environment, as well as updating them as technological development proceeds. The educational tools, which have the additional advantage of not being proprietary systems, provide the student with the real functioning knowledge of the electronic circuits involved in the project. Besides, another characteristic associated with this type of equipment construction is the flexibility to update and modify software, firmware, and hardware.

In recent years, several works have been proposed to improve and modernize the current teaching process in engineering Violante et al. (2019) - Salah et al. (2019). For instance, in the work Oliveira et al. (2019), the authors presented a tool to develop simple applications for Android-based mobile devices. They showed an application to support the teaching and learning of PLC (Programmable Logic Controller) programming. In the work Vrdoljak and Akmadzic (2019), a software solution was proposed to improve students' engineering skills in numerical modeling of the structural systems. The authors of Ribeiro et al. (2019) presented an innovative solution using augmented reality technology as a tool to improve the use of medical equipment.

Control theory is a very math-heavy subject and can be hard for the student to understand how it correlates to real-life. In the literature, a few works have been implemented to aid undergraduate students' control practice. For instance, the work of Yamagata and Morita (2017) presents an underwater robot for learning and applying modeling techniques based on control engineering. Their experiments demonstrate that the developed system improved the efficiency of control engineering education at the university level. In Michel et al. (2018), the authors present an approach based on the team to team competition using Modeling & Simulation to teach graphical-based computer language Lab VIEW for measurement, data acquisition, and control. Their experiments only rely on simulation, and they do not present practical modules. The authors in Luchin et al. (2017) developed a system composed of an embedded controller with an analog and digital input-output interface and an inertial measurement unit to be used for robotic and control engineering prototyping and education.

1.1 Main Contributions

The present work proposes the development of an affordable and easy educational kit for control theory training. This educational kit intends to be helpful in a control laboratory as a complement to the control system theoretical classes taught to undergraduate students. With the rise in popularity of open-source hardware, the ATMEGA project was chosen by its low price implementation and the huge community that collaborates with it. By using a custom PCB with an ATMEGA, it is possible to reduce costs even more while maintaining compatibility with existing Arduino codes. The main contributions of this work can be summarized as follows:

- The development of a low-cost ATMEGA-based system as a main device for an educational tool to teach control theory.
- An easy educational tool for students to implement different control techniques to stabilize a ball inside an airflow wind tower.

1.2 Organization

The present manuscript is organized as follows. Section 2 details the proposed educational tool as well as its mathematical and construction foundations. The proposed prototype's possible applications in a few subjects in the Engineering curriculum are discussed in Section 3. Section 4 presents the experimental results obtained in the wind tower after the application of classical controllers. The concluding remarks and ideas for future works are shown in Section 5.

2. PROPOSED EDUCATIONAL MODULE

2.1 Overview

The wind tower prototype proposed in this work consists of a transparent vertical cylindrical tube, within which a light ball moves freely. The ball's position is controlled by an airflow generated by an air blower actuator attached to the upper end of the tube, as shown in the illustrative image of Figure 4.

The proposed control module's main objective is to maintain the ball stabilized in a desired vertical position h^* (height) during the wind tower operation. In this project, the ATMEGA microcontroller is used to process the data and generate the actuator's output. The system control loop, as detailed in Figure 1, includes the input signal received by an ultrasonic distance sensor (analog), and the PWM control signal.

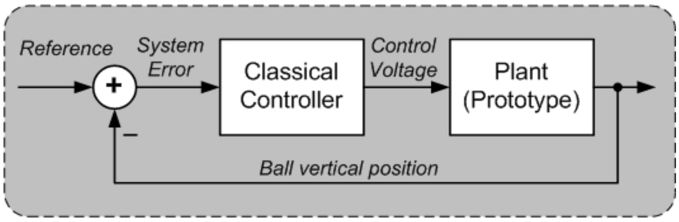

Figura 1. Diagram of the closed loop control.

As aforementioned, a circuit board was developed to control the air flow, and its schematic is shown in Figure 2. This electronic board includes:

- An ATMEGA microcontroller IC;
- A 5V reference voltage IC to provide a stable and precise voltage to the microcontroller ADC circuit;
- A mosfet to control the fan responsible for the wind tower with its optical isolator to try to mitigate any noise generated by the switching;
- A display to server as a Human Machine Interface (HMI);
- Expansion module inputs.

2.2 System Modeling

The first step is to analyze the forces that are involved in modeling the system. The basic forces acting on the ball are the gravitational force F_g and the drag force F_a. The force F_a is generated by the airflow interaction with the ball and with the tube walls. Figure 4 illustrates a simplified representation of these forces. Once the system is at equilibrium, we have that:

$$m\ddot{h} = F_a - F_g \,, \qquad F_g = mg \,, \tag{1}$$

in which m is the ball mass and g is the gravity constant. According to Chacon et al. (2017), the drag force can be described by:

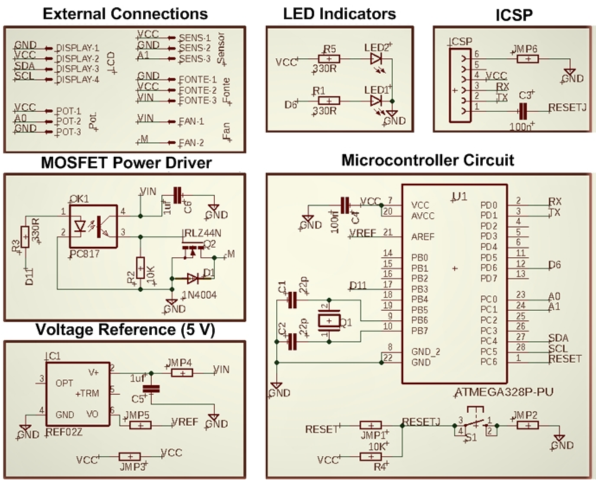

Figura 2. Schematic of the air flow control circuit board.

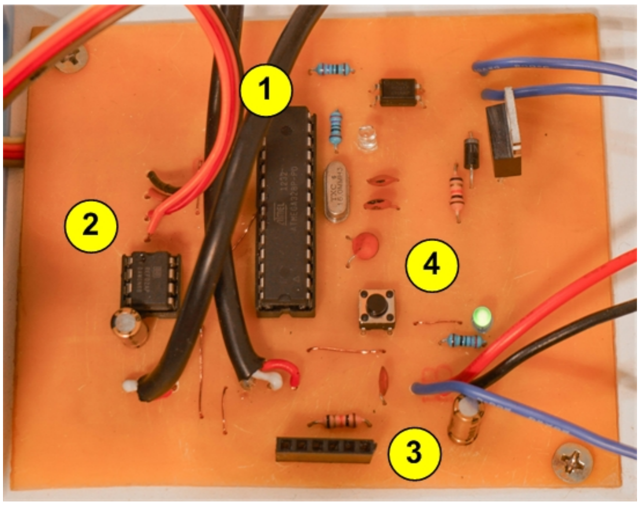

Figura 3. Assembled Microcontroller Circuit Board. 1-ATMEGA IC, 2-Voltage Reference IC, 3-ICSP Female Header Connector, 4-Reset Button.

$$F_a = \frac{1}{2} C_d A_b \rho (v_0 - \dot{h})^2 \,, \tag{2}$$

in which C_d is the drag coefficient, A_b is the ball cross-section area, ρ is the air density, v_0 is the airspeed inside the tube, and $\dot{h}$ is the vertical ball speed.

By considering small velocities of the air around the ball, one can assume that C_d is constant. Then, Equation (2) becomes:

$$\ddot{h} = \beta (v_0 - \dot{h})^2 - g \,, \qquad \beta = \frac{1}{2m} C_d A_b \rho \,. \tag{3}$$

As can be seen from Equation (3), when h stabilizes at a constant (height) value, that is, $\ddot{h} = \dot{h} = 0$, the system goes into equilibrium and then

$$\beta v_0^2 = g \longrightarrow v_0^2 = V_{eq}^2 = \frac{g}{\beta} \,, \tag{4}$$

where V_{eq} is defined as the *equilibrium point velocity* of the air inside the tube. By isolating g in Equation (4), the dynamics of Equation (3) can be rewritten as

$$\ddot{h} = g \left[\left(\frac{v_0 - \dot{h}}{V_{eq}} \right)^2 - 1 \right] \,. \tag{5}$$

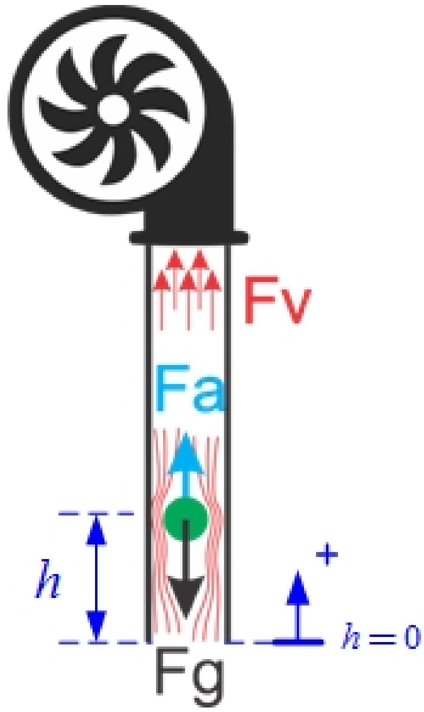

Figura 4. Representation of the forces.

As also argued by the authors in Chacon et al. (2017), the linearization of Equation (5) is straightforward to obtain by using Taylor's approximation around the point $V_{eq} = v_0 - \dot{h}$, that is,

$$\ddot{h} = \frac{2g}{V_{eq}} (v_0 - \dot{h} - V_{eq}) \,. \tag{6}$$

Assuming that the airspeed v_0 produced by the blower is dynamically related to its input voltage T_{in} by a stable first-order system, generally described by Equation (7).

$$\dot{v}_0 = -a v_0 + b T_{in} \,, \tag{7}$$

Then, the complete linearized model for the proposed prototype can be represented by the diagram of Figure 5, if we assume that this is a good approximation for the model.

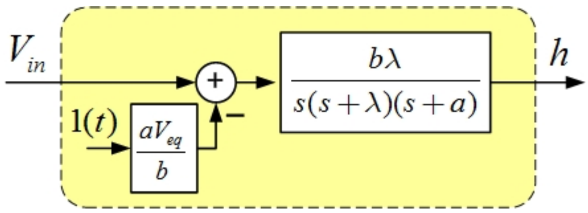

Figura 5. The model for the prototype.

In Figure 5, $\lambda = 2g/V_{eq}$ and $1(t)$ represents the unit step signal. The parameters presented in this model are related to the prototype's physical build or typical values, such as air drag constant.

3. ENGINEERING TEACHING USING THE DEVELOPED EDUCATIONAL MODULE

This work's methodology consisted of the development of a platform for experimental trials for testing control algorithms. The main objective is the possibility of being used in laboratory disciplines of control systems and automation courses. The proposed didactic kit basically consists of a bench prototype using the Atmega 328P microcontroller, an ultrasonic sensor HC-SR04, a 12V 40mm fan, and a circuit board for controlling the airflow.

In this work, the communication and control interfaces used are compatible with market and industry standards. This approach allows students to be in contact with third-party electronic components and design environments that are simple and easy to understand. The main idea is that students can develop the necessary skills and acquire knowledge to reinforce the concepts and practices that are usually required by the industry. Within this context, speed control, and related topics, all represent interesting topics in electrical, electronics and automation teaching classes, as also argued in Coşkun et al. (2019).

Currently, the control technique is a topic used in several engineering problems due to its importance in the industry. Thus, the prototype can be selected for practices in the most diverse disciplines. Table 1 presents some areas where the prototype could be applied as well as the experiments to be carried out.

4. RESULTS AND DISCUSSIONS

Figure 6 presents the constructed prototype. Note that the MOSFET driver is responsible for controlling the airflow of the wind tower. The MOSFET gate is switched through the microcontroller using pulse width modulation (PWM) to control the blower rotation. The **analogWrite** allows using a value from 0 to 255, which corresponds to 0% and 100% of the duty cycle. Therefore, the project will act directly on this value of **analogWrite**.

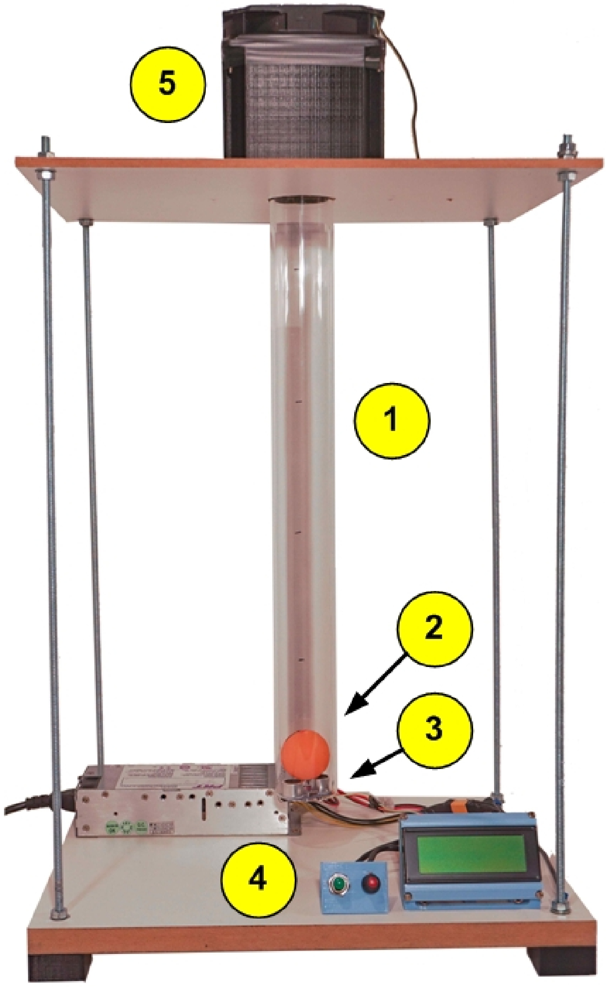

Figura 6. Built prototype. 1-Transparent Tube, 2-Light Sphere, 3-Ultrasonic Sensor, 4-Prototype Structure and Electronics, 5-Air Blower Actuator.

The next step was to test the system through different situations and controllers projected by the students. For instance, Figure 7 and Figure 8 show the implementation of a proportional (P) and proportional-integral (PI) algorithms, respectively. Note that there is still an oscillation for a PI controller, which means that the system does not stabilize enough. The authors believe that this is due to sensor response characteristics.

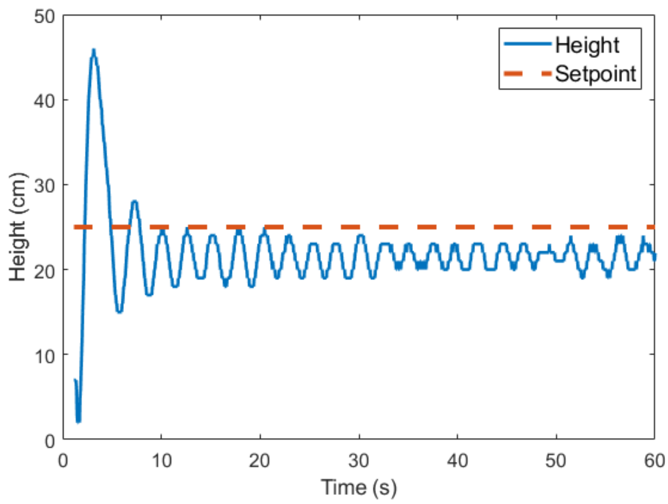

Figura 7. System response controlling one ball with a proportional controller.

Figure 9 presents the implementation of a PID algorithm controlling a ball in the wind tower. The implementation of the PID controller was also tested in different situations. For instance, Figure 10 shows this controller's performance when inserting two balls in the wind tower. Note that the system was able to follow the reference value. Another situation is illustrated in Figure 11, where the system is controlling one ball with a PID controller and low airflow.

A video of the experimental setup and trials of the proposed prototype is available at `https://youtu.be/rkyJqRMitDI`.

5. CONCLUSIONS AND FUTURE WORK

The present research paper discusses the development of a low-cost ATMEGA-based control system as a basic tool for students training on control system classes. The proposed wind tunnel prototype was assembled using available components that can be easily found in the market. From the results, it was possible to analyze the PID controller and its control action that was able to stabilize the ball's movement. The prototype can help students understand the control usage from the software

Tabela 1. Possible Applications of the Prototype in Engineering Subjects.

Lecture	Covered Topics	Experiments
Automatic Control	Controllers, signal sampling and digital signal processing.	Tuning and design of motor speed and current controllers
Instrumentation	Speed and current sensing.	Reading of sensor data, communication with applications such as Labview.
Microcontrollers	Programming of microcontrollers	Analysis of the codes involved in the prototype
Industrial Automation	Supervisory Systems	Prototype integration with a supervisory system: data reading and control

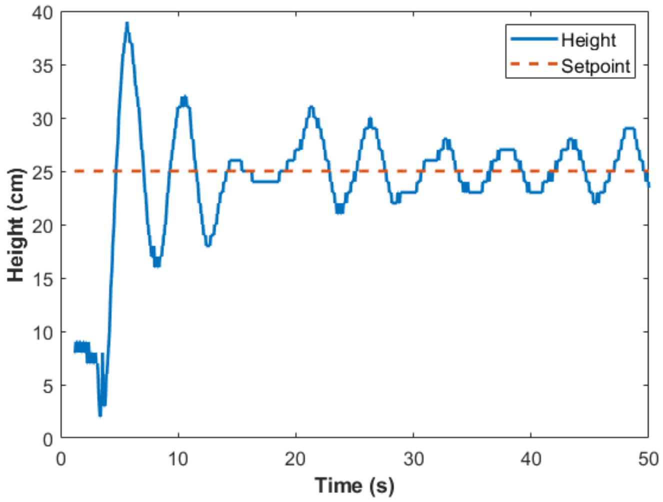

Figura 8. System response controlling one ball with a PI controller.

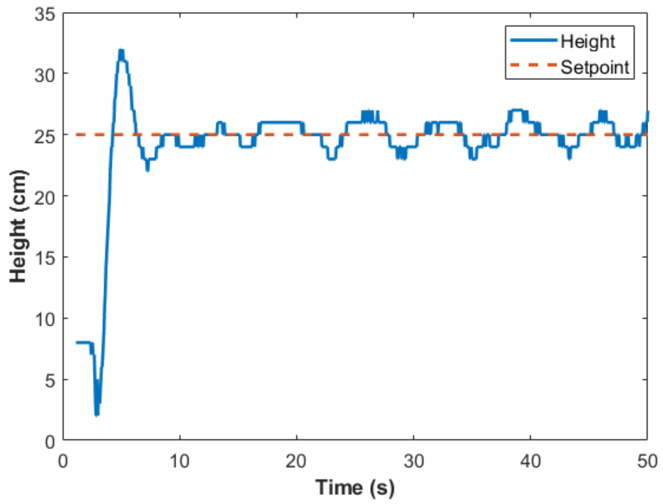

Figura 9. System response controlling one ball with a PID controller.

simulation up to the bench when they can apply the most diverse control techniques.

A few extensions are foreseen from this research work. Firstly, this project could be expanded to cover other topics, making it easy to swap modules as well as the microcontroller, which would allow different architectures and

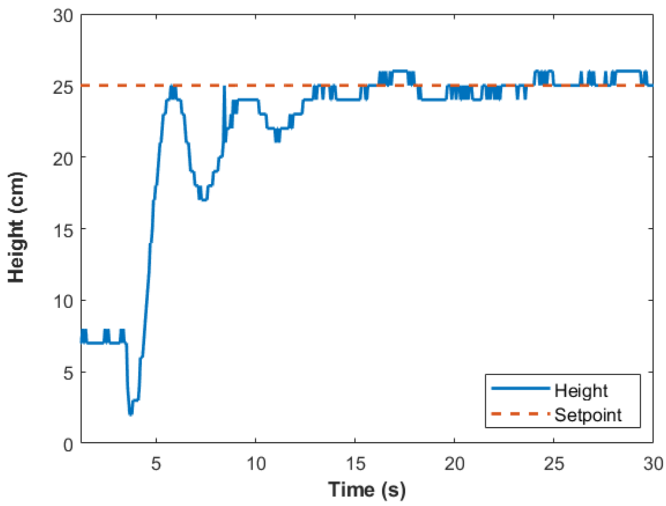

Figura 10. System response controlling two balls with a PID controller.

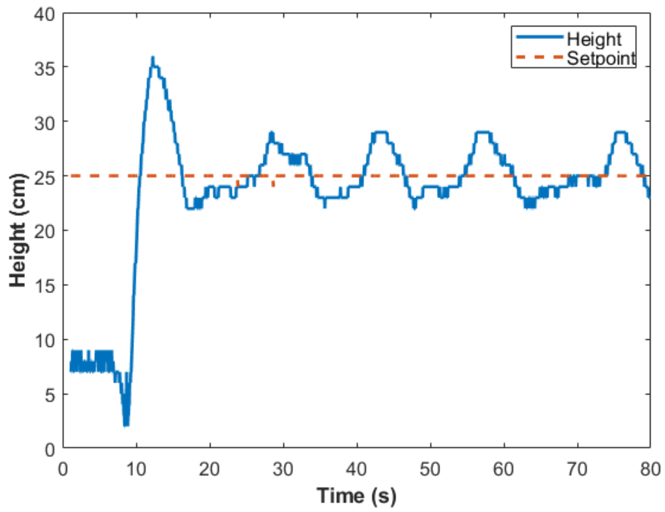

Figura 11. System response controlling one ball with a PID controller and low air flow.

programming languages to be used, such as a Raspberry Pi, ARM microprocessor, or FPGA. The prototype would also benefit from a more precise and fast distance sensor, which would feed the PID loop a more stable reading, making the project easier to adjust and obtain a lower height variation. Sensors' noise will also be evaluated and modeled to improve response characteristics. The authors also expect to develop a user interface for the project to allow easy project configuration.

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