Portable Hardware in the Loop-Based Laboratory for Advanced Control Experiments

Aldo Rafael Sartorius Castellanos[1*], José De Jesús Moreno Vázquez[1], Antonia Zamudio Radilla[1]

[1]Tecnológico Nacional de México /Instituto Tecnologico de Minatitlán, Department of Electronic Engineering
Blvd. Institutos Tecnologicos s/n, Minatitlan, Mexico

aldo.sc[at]minatitlan.tecnm.mx
jose.mv[at]minatitlan.tecnm.mx
antonia.zr[at]minatitlan.tecnm.mx

Abstract: *The increase in the online educational offer of engineering programs at bachelor and graduate levels and the decentralization and increase in education coverage in many countries pose enormous challenges for getting students to carry out activities that link theory with practice in laboratory sessions. Virtual laboratories that allow the use of specialized software in remote computers or remote laboratories, which allow the user to interact with high-cost hardware or that require special facilities, have solved part of this problem. However, there is a trend towards using portable devices or low and medium-cost kits, which can be easily assembled and replicated by both students and universities for carry out practices in introductory courses of control theory. This work presents a portable laboratory with hardware in the loop that go further and allows to carry out classic, modern, and intelligent control experiments in real time and can be replicated by educational institutions at a low cost. The proposed portable laboratory has been used and tested since 2012 by more than 300 students in bachelor and graduate courses at the Tecnológico Nacional de México campus Instituto Tecnológico de Minatitlán in the subjects of Advanced Control, Intelligent Control, and Virtual Instrumentation.*

Keywords: Advanced Control, Hardware in the loop, Portable laboratory

1. Introduction

The use of laboratories in engineering education presents significant challenges worldwide, and these challenges are due to diverse factors. For example, many public and private universities worldwide have been increased the offer of bachelor's, master and Ph. D. degrees completely online [1]. On the other hand, in many countries, mainly in the Latin-American region, universities' public educational services have been gradually decentralized, allowing education to be attended from local or regional government levels [2].

These and other factors have caused not all higher education institutions to have the same quantity, quality, and access to a laboratory for practice development, mainly in the diverse engineering fields.

Laboratories, specifically in the engineering area, have a significant impact because they allow the students to use and link the theoretical concepts with the practice. Faisel points out that engineering are a discipline and a practical profession where the key is that the students learn by doing [3]. Several solutions have been proposed to satisfy laboratory demands, and these are based on three main concepts:

1. The use of remote laboratories in diverse areas such as FPGAs (Field Programmable Gate Arrays) [4], [5], robotics [6], control systems, [7], electronics [8], and embedded systems [9], where the students interact remotely with expensive equipment or that needs specific facilities and space, achieving a considerable increase in the utilization rate of these devices [10].
2. The use of virtual laboratories where the students can perform simulations with expensive software or that needs

high-performance hardware in a remote way, such as those shown in [11] for wireless networks design, for basic electronics learning [12], or mobile robots monitoring and control [13].
3. And finally, the use of portable devices or kits of low-cost that can be easily assembled and replicated by students and universities.

The latter approach has seen tremendous growth due to the various FPGAS or microcontroller-based prototyping platforms out there. Most of these portable computers have been developed for teaching mainly introductory control theory courses.

For example, in [14], the authors propose an educational tool for introductory courses on control theory systems. This tool uses a low-cost PIC16F887 microcontroller to adjust the gains of a proportional integral derivative (PID) controller that controls a DC motor's speed. This equipment uses an analog tachometer as a speed sensor, and it's connected to the user interface using serial communication.

A similar approach, but using a dsPIC30F4012 microcontroller, is shown in [15]. This portable system allows students who have taken the first control courses to develop practices for identifying and speed control of a DC motor. In this system, the controllers must be developed using C language to be implemented in the microcontroller.

The portable systems shown in [16]– [19] are created to be used in introductory control theory courses and propose using an Arduino development board based on the 8-bit ATmega328P microcontroller from Atmel. Communication with the user interface, typically developments in LabVIEW or Simulink, is based on serial protocol. These systems are

used to control the speed of DC micromotors using a PID controller and use low-resolution optical encoders or potentiometers as speed sensors.

Some more advanced portable laboratories use development boards based on ARM microcontrollers with 32-bit architecture, allowing greater precision to read high-speed optical encoders or tachometers. These microcontrollers incorporate advanced functions for the generation of pulse width modulated (PWM) signals that allow greater motor control precision. For example, in the system shown in [20], the authors propose a portable kit to be used in introductory control theory courses. This kit uses Matlab-Simulink as a user interface and a Raspberry development board with an ARM Cortex-A72 microcontroller to identify and control a direct current motor's speed. In [21], the authors present a laboratory for introductory control theory courses based on an STM32F4 Discovery development board with an ARM Cortex M4 microcontroller. This system uses Matlab as a user interface and allows for identification and control practices on a DC motor.

Some portable devices use dedicated data acquisition cards, which simplifies system programming, but increases the cost. For example, the system shown in [22] is used for the non-linear bidirectional identification of DC motors. This system requires an Arduino development board to generate PWM signals that control the motor's speed, while the acquisition of current and position signals is made with a National Instruments DAQ-USB-602 data acquisition board. In [23], a similar approach is proposed to control the speed and analyze a DC motor's behavior. This system uses a NI-myRIO-1900 data acquisition card. Both portable laboratories use LabVIEW as the user interface and NI-DAQmx as the programming interface for easier and more integrated access to the hardware.

In this work, a portable laboratory is presented, which has been used to carry out the laboratory practices of the Advanced Control courses in the Electronic Engineering career, as well as in the Intelligent Control and Virtual Instrumentation courses in the Master's degree in Electronic Engineering at Tecnológico Nacional de México, Campus Instituto Tecnológico de Minatitlán. The architecture of the portable laboratory is presented in Section 2.

The originality of the proposed portable laboratory is that it allows practicing not only introductory control theory courses but also helps students understand the concepts of filtering analog signals, linear and non-linear identification of systems, and the design of classic, modern and intelligent control systems applied to DC motors.

The implementation of some suggested identification and control practices are presented in Section 3, while the experiences of using the system are presented in Section 4.

2. Architecture

The proposed portable laboratory, illustrated in Fig.1, consists of 5 main components:

a) A DC motor Microswitch model 22VM81-020-5 coupled with an analog tachometer.
b) Omron S82K-5024 DC power supply.
c) H-bridge based on L298N chip.
d) National Instruments data acquisition card model NI USB-6212.
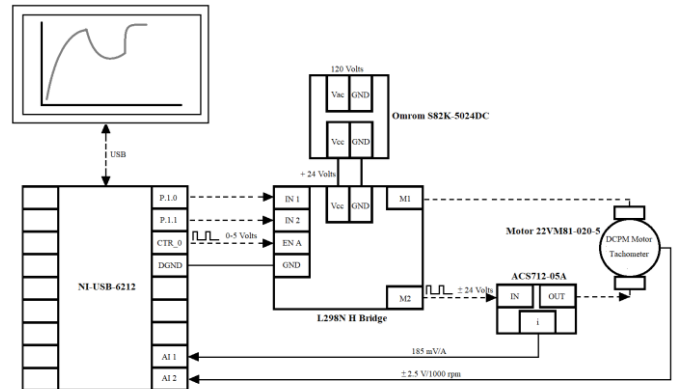e) ACS712-05 current sensor

Figure 1: General architecture and main components of the proposed portable laboratory

A. User interface

A user interface is a way by which the user can communicate with a machine, a piece of equipment, or a computer. For the proposed portable laboratory, the user interface has been developed so that the student focuses on each practice's central objective without being distracted by hardware implementation details.

A set of Simulink blocks programmed in ANSI-C language have been developed to achieve this. These blocks allow having real-time interaction with the National Instruments data acquisition card model NI USB-6212, as shown in Fig.2.

These basic Simulink blocks allow specifying the motor armature voltage in a range of $\pm$ 24 volts. According to the type of practice carried out, in an open or closed loop, this voltage can be specified by the user or by a controller.

Each practice has a sequence, so each practice provides new data that allow the next practice to be carried out and progressively increases the complexity. The sequence of operation is as follows (see Fig.1):

1. The specified voltage value is converted to an equivalent duty cycle and activates the CTR_0 port of the NI USB-6212 card, generating a PWM signal with the specified duty cycle.
2. According to the sign of the specified voltage signal, ports P1.0 and P1.1 on the NI USB-6212 board are modified to control motor rotation direction.
3. The signals on ports CTR_0, P1.0, and P1.1 control the power H Bridge, which generates the PWM signal used by the motor.
4. Analog inputs AI1 and AI2 connect the current sensor ASC712-05 and the analog tachometer coupled to the motor.
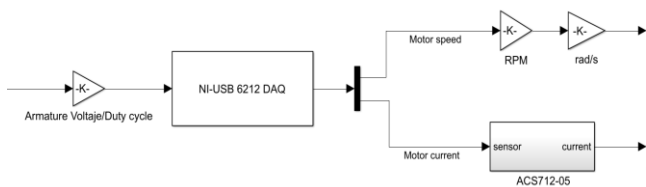
Figure 2: Simulink blocks development in ANSI C language for real-time interacting with National Instrument NI USB-6212 data acquisition card

3. Identification and Control Practices

3.1 Signal filtering

The DC motor Microswitch Model 22VM81-020-5 has an analog tachometer attached as a speed sensor. This kind of sensor has much electrical noise due to the commutator's operation, and additionally, there may have mechanical vibrations produced by a bad alignment or clamping of the motor, which affects the tachometer signal.

In Fig.3, the frequency spectrum of the Microswitch model 22VM81-020-5 motor is shown, where it is clear that at low operating voltages, have a large amount of electrical noise that affects the tachometer signal.
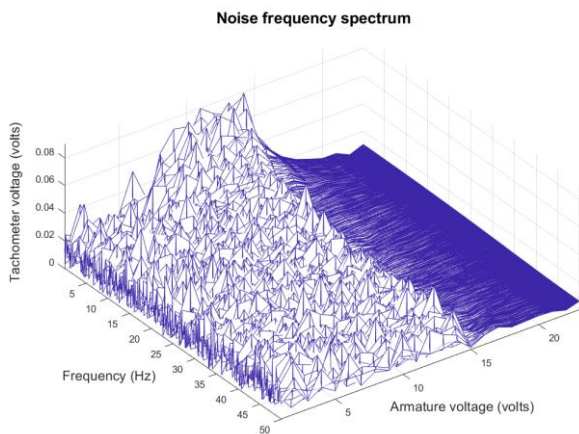

Figure 3: Noise frequency spectrum in the coupled tachometer

Therefore, the first practice that the students develop is designing a filter that achieves a cleaner signal, but at the same time, it is distorted as little as possible. The filter design can be both analog and digital. In Fig.4, the implementation of an analog low pass filter used to filter the motor's speed, and current signals is shown. Fig.5 shows both signals with and without filter implemented.
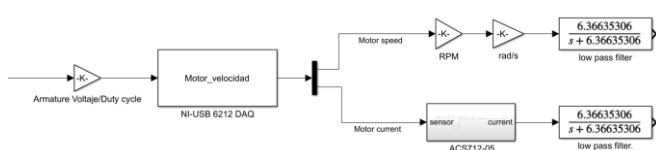

Figure 4: Low-pass analog filter implemented for signal filtering

3.2 Identification

Some controller's design methods, such as those based on classical and modern control, require a partial or complete knowledge of the system's mathematical model to be controlled and precise knowledge of the model parameters.

In this practice, students apply ramp, square, and PRBS (Pseudo Random Binary Sequence) signals to the Microswitch model 22VM81-020-5 motor and record their response, as shown in Fig.6.
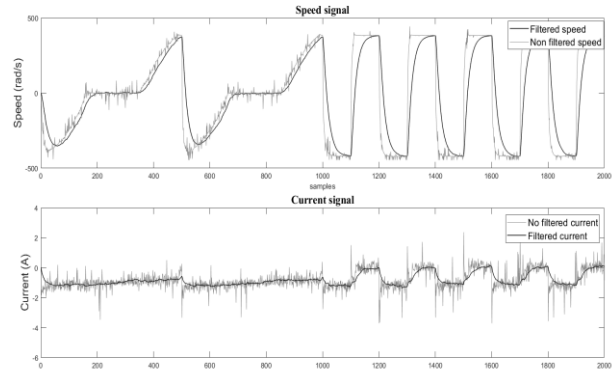

Figure 5: Filter and unfiltered DC motor's speed and current comparison.
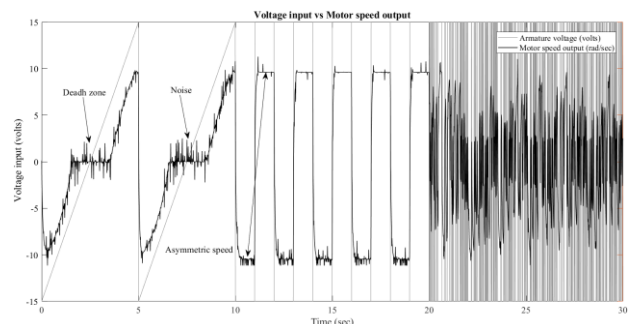

Figure 6: Ramp, square, and PRBS signals applied to DC motor for identification practices.

With these data and using the System Identification Toolbox, the students obtain a model based on a transfer function or state-space reaching around 80% similarity, as shown in Fig.7.
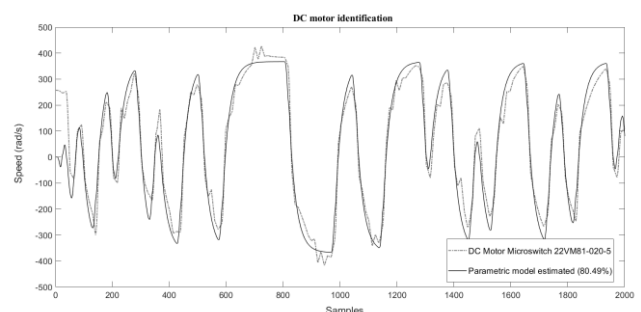

Figure 7: Response of DC motor 22VM81-02-05 against the response of the identified system

This practice has three purposes: First, the student can identify and propose different DC motor models. Second, the student can understand the effect of nonlinearities on the

response of the system. Third, the student can use these models in the following control practices simulating the controller's design and then implement their design in the portable laboratory.

3.3 State observers

In this practice, the students use the mathematical models identified in previous practices to design and implement various full and reduced-order observers, such as the one shown in Fig.8. This full-order state observer estimates the motor's speed and current from the input and output signals of the motor: the armature voltage and the motor speed, respectively.
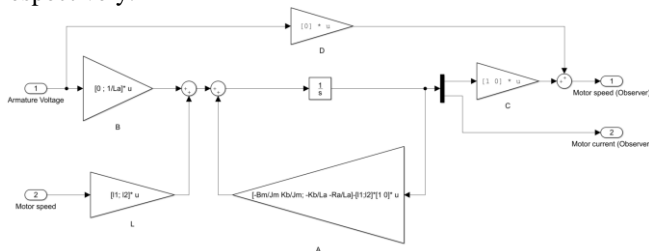

Figure 8: Block diagram of a complete state observer with two observed states for DC motor Microswitch model 22VM81-020-5

Fig.9 shows the observer's implementation in conjunction with the data acquisition blocks that allow interacting in real-time with the National Instruments data acquisition card model NI USB-6212. In this practice, a voltage signal is applied to the DC motor Microswitch model 22VM81-020-5 and allows students to compare the designed observer's output with the motor's real-time responses.
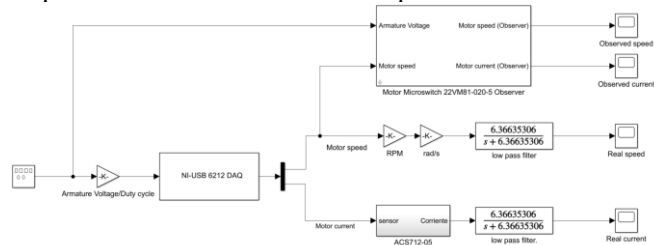

Figure 9: A full-state observer implemented with two observed states receives real-time data from the DC motor Microswitch model 22VM81-020-5.
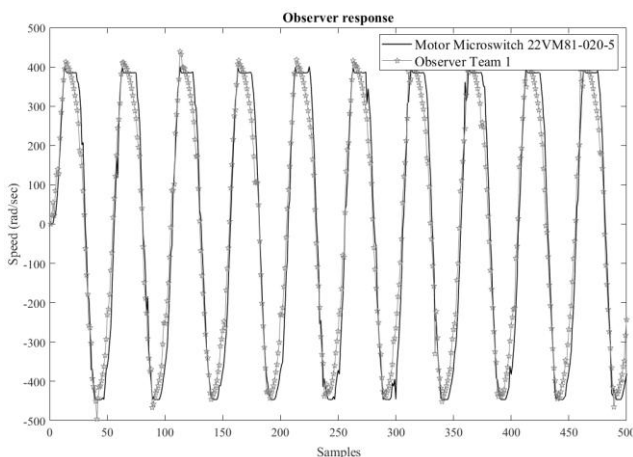

Figure 10: The DC motor Microswitch model's response model 22VM81-020-5 against the developed observer's

response to a square voltage signal with an amplitude of 20 V and a frequency of 2 Hz.

In Fig.10, the comparative responses of DC motor Microswitch model 22VM81-020-5 motor and an observer designed are shown by applying a square voltage signal with an amplitude of 20 volts and a frequency of 2 Hz.

3.4 Fuzzy control

The fuzzy and neuro-fuzzy control practices are used in the Electronic Engineering career specializing in Instrumentation and Control in Advanced Control course and the Master's program in Electronic Engineering in Intelligent Control course.

The practices that are implemented in the Advanced Control course are mainly fuzzy proportional control (FP), integral proportional fuzzy control (FPI), derivative integral proportional fuzzy control (FPID), and FPID control with an anti-windup system.

In the postgraduate course: Intelligent Control, many practices are developed that compare variants of fuzzy and neuro-fuzzy control and analyze the effects of overlaps in fuzzy sets, the increase or decrease of rules, and changes in the granularity of the sets.

For example, Fig.11 shows the response of two fuzzy controllers implemented by the students, based on a fuzzy PD + I controller with an anti-windup system reported in [24] (FPD + I AW) and a fuzzy PD controller. + I with an anti-windup system that incorporates a dynamic reprogramming of the scale factors (FPD + I AW-FSFS) reported in [25].

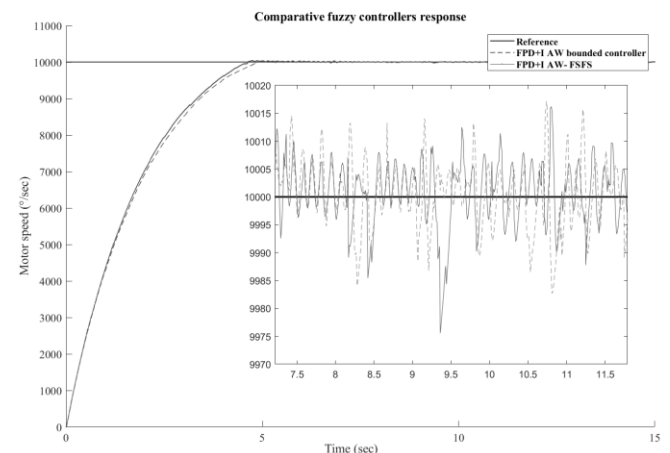**Figure 11:** Comparative response of fuzzy controllers reported in [24] and [25] implemented for control DC motor Microswitch model 22VM81-020-5 speed

4. Use experiences

The first version of the portable laboratory began to be used in the year 2012 in the Virtual Instrumentation courses of the Master's degree in Electronic Engineering to carry out the following practices:

a) Acquisition and filtering of analog signals.

b) Generation and acquisition of digital signals.
c) Generation of PWM signals for motor control.
d) Spectral analysis of analog signals.
e) Transmission of acquired signals using serial communication or TCP / IP protocol.

Later in the year 2014, the Intelligent Control course was added in the Master's degree in Electronic Engineering, and the Advanced Control course in the Electronics Engineering bachelor, where the portable laboratory has been used to carry out the practices of these two subjects:

1. Intelligent control
a) Fuzzy controller design.
b) Neuro-fuzzy systems modeling and training.
c) Neuro-fuzzy controller design.
2. Advanced control
a) State-space systems modeling.
b) Design of state feedback controllers.
c) Design of state observers.
d) Fuzzy proportional controller design.
e) Fuzzy PI controller design.
f) Fuzzy PID controller design.
g) Neuro-fuzzy controller design.

Table 1, shows the number of students who have used, tested, and helped improve the portable laboratory from 2012 to the second semester of 2020.

Table 1: Use by year of the proposed portable laboratory

Year / Course	2012	2013	2014	2015	2016	2017	2018	2019	2020
Advanced control			53	48	33	35	64	10	63
Virtual instrumentation	3	8	3	3	2	1	4	1	
Intelligent control			3	2	2	2		1	1

5. Conclusions

The use of portable laboratories that allow the student to link theory with practice and learning increases the motivation to use such equipment and even create their prototypes.

In the design of these devices, it is crucial to consider an adequate user interface, which allows the behavior of the system to be projected and thoroughly analyzed in the classroom by showing effects that the simulations do not consider, such as nonlinearities, noise, saturation, conversion errors among other factors.

This type of portable laboratory can be designed to have an open architecture in both hardware and software, which allows them to be updated and adapted to various technologies. For example, the proposed portable laboratory can use Matlab, Simulink, or LabVIEW as a user interface, which allows the creation of numerous of practices at various levels of complexity, achieving an affordable pedagogical

tool for teaching automatic control and allowing help students understand the principles of control theory.

A new version of the portable lab is currently being worked on, which uses 32-bit ARM Cortex microcontrollers instead of a data acquisition card and a Python-based user interface, which would significantly reduce costs and allow it to can be replicated by students to create their own portable laboratory.

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Author Profile

Aldo Rafael Sartorius Castellanos He received the B. S degree in Electromechanical Engineering from the Universidad Veracruzana (UV) in 2000. He received the MSc and Ph. D. degrees in Automatics from the Universidad Central de las Villas (UCLV) in 2002 and 2005, respectively. He currently works as a full-time Professor at the Tecnológico Nacional de México campus, Instituto Tecnológico de Minatitlán (TecNM / ITM) and collaborates as a visiting professor at the Centro de Tecnología Avanzada (CIATEQ). His research lines are focused on the automation and control of electromechanical systems using embedded systems.

José de Jesús Moreno Vázquez He obtained a B. S degree in Electronic Engineering from the Instituto Tecnológico de Minatitlan, Veracruz, Mexico, in 1995. He received the MSc degree from the Centro Nacional de Investigación y Desarrollo Tecnológico National (CENIDET) in 1996 and the Ph. D. degree in Bioengineering from the Universidad Politécnica de Valencia in 2011. He is currently head of research projects in the Department of Electronic Engineering and professor of the Master's degree in Electronic Engineering. His current interests are digital systems, digital signal processing, bioelectronics, and instrumentation.

Antonia Zamudio Radilla She was born in Distrito Federal, México. She is graduated from Instituto Tecnológico de Minatitlán, in Veracruz, México, graduated in 1988 in Electronic Engineering. She has received MDU degree in Educatión from Universidad Iberoaméricana Golfo Centro in Puebla México in 2012. She has worked in C. P. Cangrejera at Petróleos Mexicanos PEMEX Company in the field of automation and control in Coatzacoalcos Veracruz, México. Since year 1984 she has been working as a full-time professor in electronic engineering career at Instituto Tecnológico de Minatitlan in México. Since year 1992 she has been working as professor in Universidad Veracruzana in Minatitlan, Mexico. MDU. Zamudio is member of Institute of Electrical and Electronics Engineers (IEEE) and his interests include Analog Electronic and Education.