IJIREEICE

ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

International Journal of Innovative Research in
Electrical, Electronics, Instrumentation and Control Engineering

ISO 3297:2007 Certified

Vol. 5, Issue 2, February 2017

Servo-In-A-Box

Hai T. Ho

Theodore Grosch, Kennesaw State University

Abstract: Lack of remote access to engineering laboratory systems has prevented distance learning from fulfilling the accreditation requirements of hands-on design and implementation experience. Although there have been solutions developed around remote and virtual laboratories, these solutions do not fulfill the simultaneous requirements of being portable, plug-and-play, low cost, and commercially available. In this paper, we propose a product oriented solution of a low-cost hardware lab system that every student can own and conduct their laboratory experiments at any location. We introduce a control system lab platform called servo-in-a-box, which is an integrated electro-mechanical servo system, complete with DC motor, sensor, power driver, USB interface, and software. This servo-in-a-box enables many undergraduate control engineering students to conduct PID hardware control lab remotely and individually, while meeting the hands-on learning objectives associated with a traditional on-campus laboratory.

Keywords: portable, plug-and-play, low cost, DC motor, sensor, power driver, USB interface, and software.

I. INTRODUCTION

Motion control systems are virtually everywhere including our homes, public places, and factories. Some examples are home robotic vacuum cleaners, elevators, wind turbines, vending machines, drones, and robotic manipulators used in manufacturing lines. All these systems have DC motors that enable the motion to occur. Therefore, it is fundamentally important to teach DC motor servo control in undergraduate control system courses. Usually, both the theory and lab components are covered in order to achieve complete learning experience. The widely used text book authored by Nise [1] covers the details of the electromechanical servo system modeling and simulation, and references a rotary servo lab system made by the company Quanser [7]. These lab hardware systems, along with others similar to it, were developed for campus laboratories where they can handle heavy long term use; therefore the dollar costs are very high. This has been an acceptable arrangement for traditional learning model where students come to campus to conduct laboratories, often times in groups due to limited number of stations.

However, with the proliferation of distance learning degree programs, there have been ongoing efforts to figure out how to enable hands-on lab experience remotely [1-4, 10-13]. Many online engineering programs failed to obtain ABET accreditation [8] due to lack of hands-on laboratories. As a result, there have been studies on remote and mobile hands-on learning models [14, 15] where pedagogy benefits were pointed out. The models that are most relevant to this paper are the student-owned equipment lab courses and the mobile studios. There is a category of remote labs where students use remote access to operate lab apparatuses that are housed on campus [1-4].We do not see much future of such remote labs as they are normally not robust and require high maintenance. However, in recent years, there have been a few solutions proposed as portable lab kits that are promising.

We contend that in order for a portable control engineering lab system to be broadly effective, it should have the following characteristics: a) low cost at less than $50/unit, b) plug-and-play that avoids assembly and hardware debug, c) not require expensive commercial software such as Matlab, and d) can be commercially produced to provide to large number of students. With a solution that meets these a-d requirements, students can achieve the necessary hands-on lab learning objectives working individually or in a group, anywhere, anytime. In surveying existing recent literature, there were several DC-motor servo control lab systems. The first is a commercial system made by Quanser, the Servo QUBE™ [6]. This system is portable plug-and-play and robust but at a very high cost point greater than $1k, and it requires Matlab. Another proposal was a system based on off-the-shelf microcontroller board dsPIC and discrete drivers and interface electronics [10]. This solution does not require Matlab, but involves assembly and do not meet the low cost threshold. The entire system costs $80 without motor and power supply, which could add another $20. Similarly, the solution in [12] requires assembly but not Matlab. A very recent proposal is [11, 13], which is based on also off-the-shelf popular microcontroller board, RaspberryPi®, and discrete electronics and motor. This setup requires assembly and debug, Matlab, and has the parts cost of $125. Out of all these systems, only the Quanser QUBE™ is commercially available.

Here, we outline a portable hardware control system lab that meets all the requirements a-d while achieving key hands-on learning objectives. Following the terminology used at Virginia Polytechnic Institute, “Lab-in-a-box” [16], we propose the servo-in-a-boxstudent-owned lab system, which consists of a DC motor with optical encoder, power driver, system-on-chip (SoC), interface software, and lab manuals. This control system is shown in Figure 1.All the

IJIREEICE

ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

International Journal of Innovative Research in
Electrical, Electronics, Instrumentation and Control Engineering

ISO 3297:2007 Certified

Vol. 5, Issue 2, February 2017

parts are housed in a box with only the motor shaft/arm and the USB connector exposed. The total parts cost is approximately $25. This is achieved by custom designing the electronics to avoid the overhead high cost of off-the-shelf microcontroller board. An external power supply is not necessary as the motor is low power and can draw the power from the USB port of the laptop. The system is designed to support basic control configurations such as PID and system identification. The software is custom application with an API-based user interface that provides basic plotting and setting of controller parameters. Lastly, the design of the servo-in-a-box is intended for commercial production. Note that although the parts cost is low but the engineering development cost is significant. Companies make profits by investing in development while aiming to sell many units at reasonable price point.

II. OBJECTIVES OF HARDWARE CONTROLS LAB

A. Technical Objectives

The following are the technical hands-on learning objectives of amotion control system laboratory:

1. Modeling of electromechanical servo plant.
2. Specifying design performance targets such as settle time, steady sate error, damping, and bandwidth.
3. Design controller, such as PID, to meet specifications. Verify with simulation.
4. Validating plant model with hardware setup that includes DC motor and driver.
5. Implement and debug real-time control system.

B. Laboratory Objectives

Unlike simulations, hardware labs give real-world-like experience because students work on physical components and witness real-time signals and responses. They further observe the effects of real world constraints and limitations such as voltage saturation and mechanical nonlinearities. The following are objectives of a servo laboratory lab system:

1. Consists of motor, driver, and position sensor.
2. Consists of a micro controller that is capable of performing real-time execution of the control algorithm.
3. A connected computer/laptop with GUI software to allow user to program the servo system, collect and plot real-time signals.
4. Hands-on debug and operation.
5. Lab instructions to guide design and implementation of the servo control system.

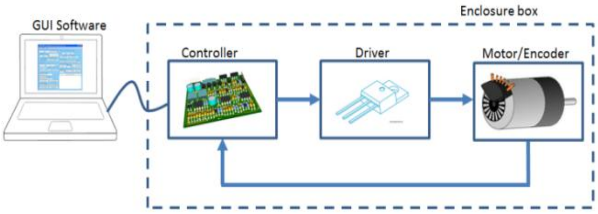

Figure 1. Layout of servo-in-a-box

These objectives are aimed to be equivalent to an on-campus traditional servo lab such as the Quanser rotary servo [7].

III. ARCHITECTURE AND DESIGN

A distance learning laboratory kit must meet the objectives stated above at minimal cost to reach as many students as possible. There are other home-laboratory products and kits that are priced in the range of a typical textbook. Processing platforms such as the Arduino®, RaspberryPi®, and Beaglebone®, and Einstein come to mind. USB powered oscilloscopes and logical analyzers provide excellent starter tools for distance learning. The research presented here has two objectives: to facilitate distance learning in control theory; to provide an affordable turn-key platform. The downside of using a off-the-shelf development kit to build a portable lab system is the higher cost and assembly [11, 13]. Our approach is to custom design the hardware with minimal part cost.

The servo box includes a motor, encoder, driver, and interface electronics. The interface could be used in conjunction with a PC sound card, but most laptops do not have a full sound card interface. The secondchoice is using the USB interface, which implies a microcontroller as an interface in the box, which is capable of serving as the loop controller as well. To minimize the cost to the student, the Servo-in-a-Box is includes everything on the right side of the laptop computer in Figure 1 in a single package only the motor shaft, an LED, and USB port exposed.
The function of the PC on the left of Figure 1 is to accept user input and help the student work with the data. Any general purpose PC, laptop, or tablet with a USB port can be used with a suitable application, even a simple terminal program.

A. Architecture

In any practical system, the control loop can be implemented in the PC or in the servo box. Closing the loop in the PC has the advantage of versatility, but can put the burden of higher cost on the student in terms of performance or software such as Simulink®. For the Servo-in-a-Box, the control loop is closed in by the controller firmware, which runs a general-purpose control loop that can be configured and operated through an open Application Programming Interface (API). The basic system comes with a Graphical User Interface (GIU) for the student's PC. The student need not purchase or own any other equipment or software, however plug-ins for programs like Simulink® and Exel® can interface with the controller through the API via the USB port. This all serves to lower the cost of ownership while maximizing functionality for the student.
In the basic instructional scenario, the student chooses the experiment, enters the stimulus and control parameters. The PC application displays and assists the student in analyzing the data.

DOI 10.17148/IJIREEICE.2017.5211

IJIREEICE
ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526
International Journal of Innovative Research in
Electrical, Electronics, Instrumentation and Control Engineering
ISO 3297:2007 Certified
Vol. 5, Issue 2, February 2017

For example, in the position control learning exercise, the student is given the transfer characteristic of the motor/shaft in rad/s/V. The instructions state the step response and design goals of rise time, overshoot, and setting time of the control system.

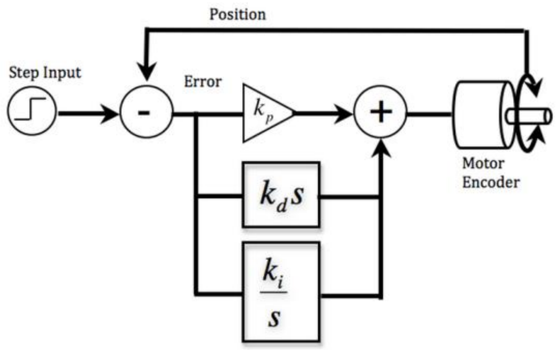

Figure 2 Example PID control system

The student must then determine the PID coefficients as shown in Figure 2, enter these in the Servo-In-A-Box application on the PC or laptop. This data is sent to the controller in Figure and, the loop is closed. The controller sends shaft position and control voltage data to the PC after closure. The Servo-in-a-Box application graphs the data and helps the student analyze the response. In addition, the student can manually rotate the motor shaft, feel the torque increase, see the LED get brighter, and observe the loop in action when the shaft is released. All the time, the application is displaying position and control data in a moving graph.

B. Hardware and Software Design

The basic system consists of the hardware components shown in Figure 1, firmware running in the controller, and an application on a PC or laptop. Figure 3 is a photo of the prototype hardware and the schematic is shown in Figure 4. The bill of materials (BOM) is shown in Table 1 and suggests that the cost of the servo box will be affordable as it is much less than the cost of a text book.

Table 1. Bill of materials of key components

Servo-in-a-box BOM		
	Part Description	**Estimated Cost ($)**
1	TB6612FNG H-Bridge Driver	1.27
2	CY8-4200 ARM Processor System on a Chip (PSoC)	2.30
3	CP2102 USB to serial interface chip	2.30
4	DC Motor/Encoder	12.64
5	Enclosure	2.30
6	PCB	2.40
7	LEDs	0.60
8	USB cable	2.00
	Subtotal	**25.81**

There are multiple ARM-based system-on-chips (SoC) that can be used to develop a low cost electronics controller platform shown in Figure 1. When choosing a suitable microcontroller, we considered cost, speed, floating-point core, and a possibility of a hardware quadrature decoder. The current model has a Cyprus SoC with a Cortex M4 processor.

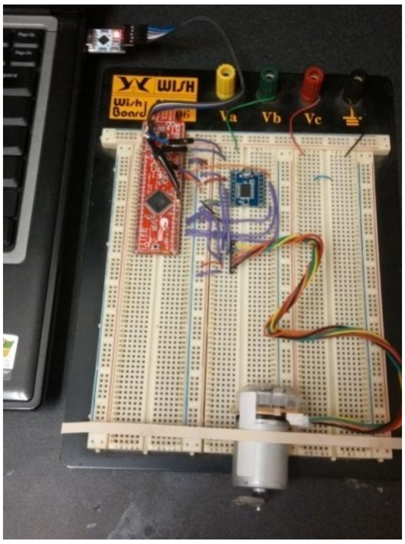

Figure 3. Photo of prototype hardware

The driver is an integrated H-bridge that provides forward or reverse current to the motor. The controller firmware sets up and controls a pulse-width-modulator and the H-bridge with the control algorism as to the pulse width, motor direction and breaking. The motor is a low-cost DC motor with a quadrature encoder with which shaft position and direction is measured.
The control loop is closed by the ARM controller firmware and loop parameters sampled at approximately every millisecond. The PWM output also drives an LED where the student has a visual indication of how hard the motor is being driven in real time. Once the control loop is closed, data is streamed to the PC Servo-in-a-Box application on the PC.
The Servo-in-a-Box application serves to interface with the student and assist in measuring loop performance as shown in Figure 5. A standard USB port is required that can supply power to the servo box and transfer data to and from the box.

The user chooses the control scenario and enters the necessary parameters. These are sent to the controller and the loop is closed. Data is streams to the application for analysis and control. The user can then change the mode, change parameters, or stop the loop at any time. Figure 6is a plot of a step function of π radians as executed by the prototype hardware.
Also important, the student has the option to use a higher-level applications to design and simulate the loop, then load the stimulus and parameters with API calls. If the student has Simulink®, the control system can be designed,

IJIREEICE
ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526
International Journal of Innovative Research in
Electrical, Electronics, Instrumentation and Control Engineering
ISO 3297:2007 Certified
Vol. 5, Issue 2, February 2017

simulated, and tested with the servo-box using a plug-in that interfaces with the controller API.

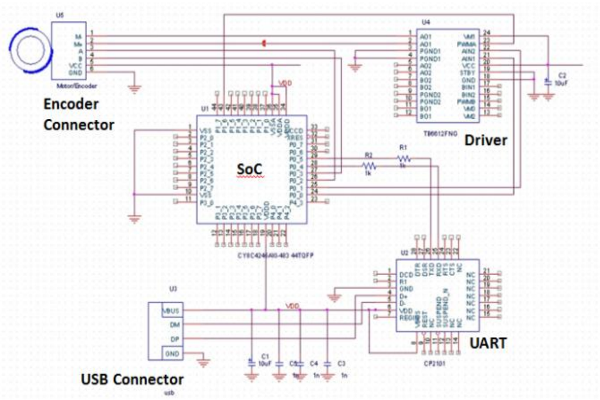

Figure 4. Low cost electronics schematic

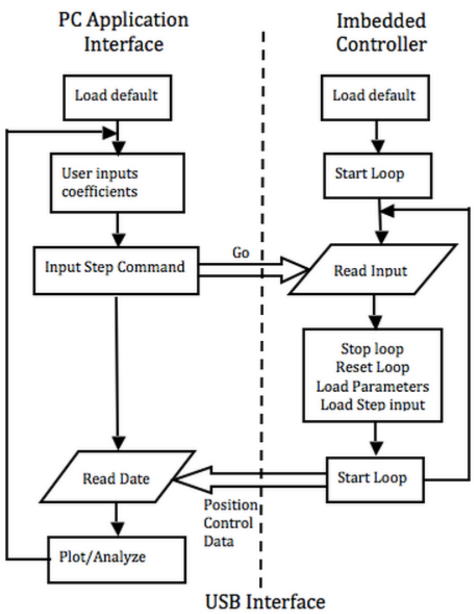

Figure 5. Example PID control system

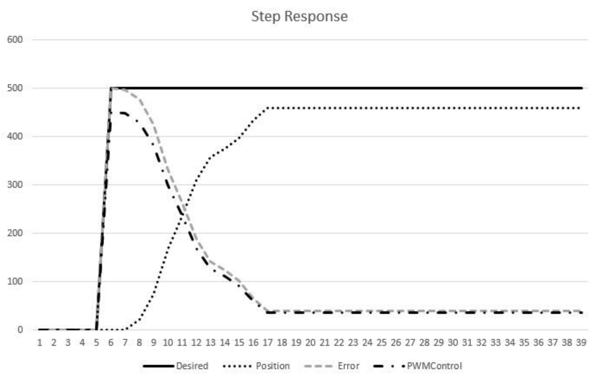

Figure 6. Example plot of the actual motor step response

C. Laboratory Manuals

The technical objectives stated in section I.B can be met with using the servo-in-a-box lab along with the following lab exercises shown in Table 2. Similar to the labs proposed in [11], the learning objectives are met buy gaining understanding of the DC motor dynamics and control. Students start out with first lab where they derive the transfer function of the plant based on schematic and parameters of DC motor obtained from datasheet. The next proceed to simulate the plant with some test signal such as square wave. Then in the second lab, plant validation with using the same test signal to drive the hardware servo-in-a-box. The responses of the system is measured and compared against the simulation to validate the plant model. The students then next design and/or tune a PID closed loop system to meet the performance objectives such as settle time, overshoot, and maximum input voltage. This design is simulated to confirm that it met the objectives. The fourth lab is about implementing the PID on the hardware system then verification of results. Lastly, the fifth lab involves measuring the frequency response of the system. It should be recognized that most of the important objectives of a hands-on control laboratory can be met through this system and lab exercises.

Table 2. Lab series for servo-in-a-box kit

	Lab Exercise
Lab #1	Plant modeling and simulation
Lab #2	Plant validation
Lab #3	PID design - simulation
Lab #4	PID design - implementation
Lab #5	Frequency bode response

IV. CONCLUSION

There is a need for remote and portable labs that accommodate distance and individual learning while achieving actual hands-on objectives. We proposed a portable servo lab kit that is low cost and with complete functionality. The concept and architecture of the Servo-In-A-Box are presented in this paper. The prototype demonstrated that closing the servo loop using a PID controller was quite straight forward and the experience was enriching. In order for the complete benefits to be realized, the system needs to be productized and made available to students taking undergraduate control system classes.

REFERENCES

[1] Nise, Norman S. CONTROL SYSTEMS ENGINEERING, (With CD). John Wiley & Sons, 2007.
[2] Ionescu, Clara Mihaela, Ernesto Fabregas, Simona M. Cristescu, Sebastian Dormido, and Robin De Keyser. "A remote laboratory as an innovative educational tool for practicing control engineering concepts." Education, IEEE Transactions on 56, no. 4 (2013): 436-442.
[3] Odeh, Salaheddin, and EimanKetaneh. "E-collaborative remote engineering labs." In Global Engineering Education Conference (EDUCON), 2012 IEEE, pp. 1-10. IEEE, 2012.
[4] Lerro, F., S. Marchisio, S. Martini, H. Massacesi, E. Perretta, A. Gimenez, N. Aimetti, and J. I. Oshiro. "Integration of an e-learning

platform and a remote laboratory for the experimental training at distance in engineering education." In Remote Engineering and Virtual Instrumentation (REV), 2012 9th International Conference on, pp. 1-5. IEEE, 2012.

[5] Singh, A. K., S. Chatterji, S. L. Shimi, and A. Gaur. "Remote Lab in Instrumentation and Control Engineering Using LabVIEW." (2015).

[6] ----, QUBE™-Servo, http://quanser.com/products/qube_servo, Quanser Corp.

[7] ----, Rotary Servo, http://quanser.com/Products/rotary_servo, Quanser Corp.

[8] Felder, Richard M., and Rebecca Brent. "Designing and teaching courses to satisfy the ABET engineering criteria." JOURNAL OF ENGINEERING EDUCATION-WASHINGTON- 92, no. 1 (2003): 7-26.

[9] Jara, Carlos A., Francisco A. Candelas, Santiago T. Puente, and Fernando Torres. "Hands-on experiences of undergraduate students in Automatics and Robotics using a virtual and remote laboratory." Computers & Education 57, no. 4 (2011): 2451-2461.

[10] Gunasekaran, Manavaalan, and Ramprasad Potluri. "Low-cost undergraduate control systems experiments using microcontroller-based control of a dc motor." Education, IEEE Transactions on 55, no. 4 (2012): 508-516.

[11] Reck, Rebecca M., and Ramavarapu S. Sreenivas. "Developing a new affordable DC motor laboratory kit for an existing undergraduate controls course." In American Control Conference (ACC), 2015, pp. 2801-2806. IEEE, 2015.

[12] Stark, Brandon, Zhuo Li, Brendan Smith, and YangQuan Chen. "Take-home mechatronics control labs: a low-cost personal solution and educational assessment." In ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, pp. V004T08A036-V004T08A036. American Society of Mechanical Engineers, 2013.

[13] Reck, Rebecca M., and Ramavarapu S. Sreenivas. "Developing an Affordable Laboratory Kit for Undergraduate Controls Education." In ASME 2014 Dynamic Systems and Control Conference, pp. V001T02A004-V001T02A004. American Society of Mechanical Engineers, 2014.

[14] Connor, K. A., B. Ferri, and K. Meehan. "Models of mobile hands-on stem education." In 120th ASEE Annual Conference and Exposition. 2013.

[15] Droge, Greg N., Bonnie Ferri, and Jilll L. Auerbach. "Distributed Laboratories: Control System Experiments with LabVIEW and the LEGO NXT Platform." In American Society for Engineering Education. American Society for Engineering Education, 2012.

[16] Hendricks, Robert W., Ka Ming Lai, and James B. Webb. "Lab-in-a-box: Experiments in electronic circuits that support introductory courses for electrical and computer engineers." age 10 (2005): 1.