MultipurposeLow-Cost Hardware Laboratory Setups inEngineering Education

S. Gross
Education Technical Specialist
The MathWorks GmbH
Ismaning, Germany
E-mail:sebastian.gross@mathworks.de

D. Weida
Application Engineer
The MathWorks GmbH
Ismaning, Germany
E-mail: daniel.weida@mathworks.de

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INTRODUCTION

Solid theoretical foundations are necessary for any kind of engineering or scientific education. This has been stressed by many engineering education societies and institutions such as the European Network for Accreditation of Engineering Education (ENAEE)[1], the National Academy of Engineering[2], the Stationery Office (Great Britain) and Technology Committee[3], and the CDIO Initiative[4].

However, they also state that students benefit greatly from applications and practical examples to supplement their learning. ENAEE[1] requires engineering practice, the National Academy of Engineering[2] calls for the exploration of case-studies and real-world problems, and the CDIO Initiative[4] issued standards for Active Learning and Engineering Workspaces. Especially in engineering education, problem-based learning and laboratories are a centrepiece of higher education curricula.

The rest of the paper is organized as follows. Section 1 revisits scientific literature on teaching laboratories, hands-on learning, and experience-based learning. Based on these remarks, Section 2 proposes multipurpose use of low-cost hardware to overcome many shortcomings of traditional laboratory setups. Section 3 introduces a modular laboratory setup example with aspect from controls, communication, image processing, measurement, and other fields using Arduino Uno and Raspberry Pi. Section 4 summarizes the paper and highlights future steps.

1 BACKGROUND, SCIENTIFIC PAPERS

Thissection discussesthe reasoning for laboratories and several of their drawbacks, as well as options for the evolution of laboratories.

1.1 Why laboratories?

Laboratories are a centrepiece of engineering education. Flick[5] refers to the introduction of hands-on activities as a revolution in education. He argues that it represents the move from an empiric (based on observing) to a constructivist (based on interaction with experiments) learning approach.

Canfield[6] reports that removing lectures and adding hands-on time in a computational methods class helped to ‘equip [..] students with the critical analytical skills that companies require in engineering graduates, including the ability to use numerical methods to solve real-world engineering problems’.Gillet et al.[7] state that ‘practice is often the key to become an effective professional, and this is particularly true for engineering disciplines.’

Besides the effect on learning outcomes, laboratories also have a well-documented motivational effect. Behrens et al. [8] describe the implementation of a robotics class to motivate first-year students in the electrical engineering program at RWTH Aachen University. Knutson et al.[9] bring ‘the excitement and motivation of research to students’ with hands-on experiences.

Today’s self-evidence of laboratories and hands-on approaches is expressed by Feisel et Rosa [10]: ’The function of the engineering profession is to manipulate materials, energy, and information, thereby creating benefit for humankind. To do this successfully, engineers must have a knowledge of nature that goes beyond mere theory — knowledge that is traditionally gained in educational laboratories.’

1.2 Disadvantages of traditional laboratories

Creating laboratories takes a lot of work for the educator as well as considerable investments in hardware, software, materials, and other infrastructure. Furthermore, running a lab class regularly requires more staff than giving lectures does. The content progress in a lab class setting is also not as tightly controlled as in lectures, while the penetration depth may vary between different student groups.

1.3 Virtual laboratories

One of the possible solutions for some of these problems is the creation of virtual laboratories, or even remote laboratories, where students can access a lab setup over computer networks. Thus, a single setup can be used by several lab groups as well as across different classes. This can happen independently of lab infrastructure and time. However, it means that students have no physical access to the hardware and the setup might add little when compared to simulation.

Gillet et al.[7] discuss virtual laboratories for long-distance and asynchronous learning. They argue that ‘these solutions provide students with more flexibility in both time and place, and reduce the campus infrastructure needs’. Triona et Klahr[11] raise the question whether this form of laboratory should actually be called hands-on or hands-off instruction. While they conclude that virtual laboratories are an efficient teaching method ‘(i.e., take less time to develop and resources to develop and use)’, they admit that ‘there might be particular domains (e.g., life sciences) that require experience with authentic, physical objects rather than their virtual equivalents’[11].

Feisel et Rosa[10] describe the use of simulation to real-life experiments in flight training as early as 1928 to reduce cost and risk of training. However, they also comment that ‘real devices and materials are intricate and difficult to model accurately. […] Understanding the limitations of simulations compared to real processes is a key factor in their use. […] It is generally agreed that computer simulations today cannot completely replace physical, hands-on experiments.'[10]

Davis [12] cites Zipporah Miller, associate executive director for the National Science Teachers Association: "If they go through simulation, they may get the right answers […], but they may not have the experience to apply that knowledge in the real world."[1]

1.4 Low-Cost Hardware

Another solution to reduce overall hardware costs and infrastructure needs is to use low-cost mass market hardware. This hardware is widely available and has become very popular in recent years with the rise of LEGO MINDSTORMS, Arduino platforms, Raspberry Pi, and countless others.

With inexpensive experiments, individual student groups, or even individual students, can have their own hardware and gain real hands-on experience. Potentially, students could take small and inexpensive hardware home to free them from time and distance constraints while still having access to real-life experiments.

Some institutions have moved from onsite lab classes to home study with student-owned experimentsusing Arduino[13] or Raspberry Pi[14].

2 MULTICONCEPTIONAL LOW-COST HARDWARE LABORATORIES

In this section of the paper, we propose that a single laboratory setup can often be used to demonstrate more than one concept. Thus, a mass market, low-cost hardware setup can be leveraged across different classes, labs, and disciplines.

2.1 Student affordable hardware

Using low-cost hardware reduces the overall hardware costs. Some of the platforms are in a price range that enables classes/universities to give a hardware set to every individual student or student group. This allows for 'real' hands-on experience instead of 'hands-off' virtual simulation.

Some universities[13] reuse demo setups often and throughout degree programs. They require their students to buy the hardware and software to provide them with a flexible and powerful tool for their learning. This hardware can consequently not only be used in laboratories, but also at home and anywhere else students want to work on their projects, and at any time the students see fit.

2.2 Modular development and learning

A modular development of laboratories allows educators and students to leverage previously used hardware and software setups by adding or replacing elements for different classes, while reusing familiar and reliable structures. Thus, the need for creating a new setup with installing and configuring hardware, as well as supplying software for every new class, is removed.

Educators can focus on teaching their topics instead of designing experimental environments and instructing their students on the use of these. Students can build on earlier experiences and dig deeper into the topics at hand.

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[1] This also highlights the difference between the application of simulation tools in education and a professional setting where users have the background to use the tool to a greater extent.

2.3 Employing industry tools

Continuoususe of a familiar software tool chain, as well as standard hardware, supports teaching and learning in higher level education and ensures the proficiency of students in the use of industry standard tools[15, 16, 17].

Students and educators alike value the faster starts into new topics, without adjustments to new environments, resulting in more time to discuss important topics and discover more complex schemes and scenarios[15].

In addition, transitioning to a career after graduationis simpler if students can reliably work with the tools that are in use throughout their target industries[15, 16]. This increases their employability and eases their start into the rest oftheir lives. Furthermore, the education institution gains a reputation for high-value education, increasing the international standing with both potential students and industry partners.

3 EXAMPLE

In this section, we present a hardware example employing a Raspberry Pi and an Arduino Uno. We discuss the configuration and elaborate on the different focus fields than can be taught by working with a single setup.

Figure 2: Exampledemo setup using Arduino and Raspberry Pi

3.1 Overview

As an example, we present a system of two embedded systems that automatically analyses video footage and track a ball with a camera. The setup shown in Figure 1 consists of an Arduino Uno R3[18]to control the motor that turns the camera, and a Raspberry Pi Model B[19]thathandles imaging and image analysis. The example can be used as a laboratory exercise for image acquisition and processing, controls, parameter tuning, system identification, testing, and deployment on embedded platforms. Several modular steps are depicted in Figure 2.

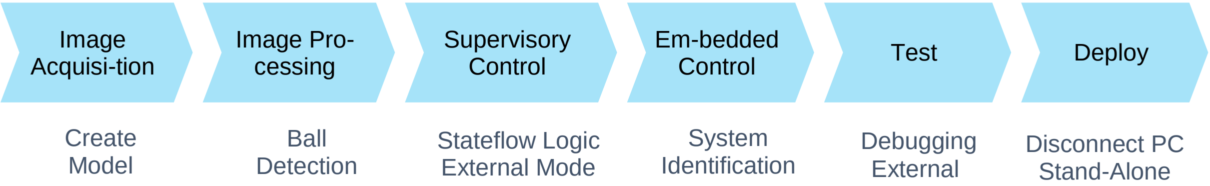


Figure 1: Modular structure of demo setup

3.2 Image acquisition and object tracking

The first step in the process chain is image acquisition. In our setup, a regular off-the-shelf USB camera is attached to the Raspberry Pi. The image is acquired using a simple interface block in Simulink, the graphical model-based design environment.

The image is then analysed in the second step where a green ball in the image acquired by the Raspberry Pi is detected. If the ball is present, then the x-coordinate on the image plane where the ball is located is forwarded to the latter control algorithms. Astraightforward Simulink model that performs the detection and segmentation task is shown inFigure 3. Possible extensions of this module include detection of other shapes and colours or more sophisticated approaches like face detection.

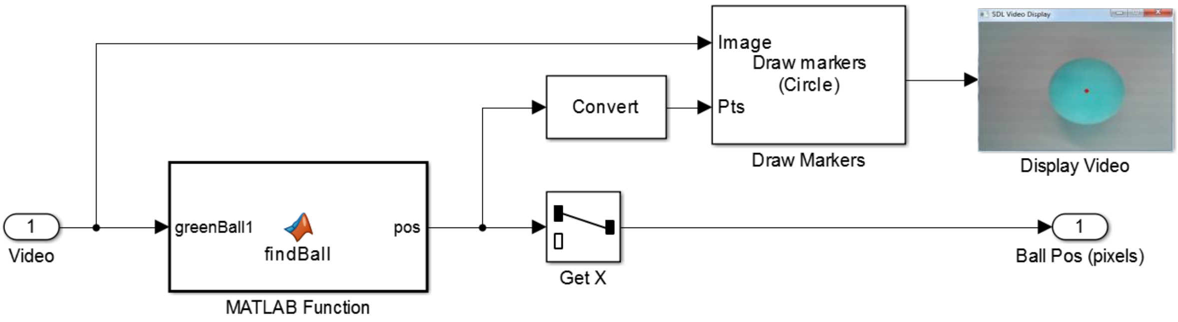


Figure 3: Detecting the center of a green ball in the image acquired by the Raspberry Pi

3.3 Controlling different operational stages of the demo setup

The next module in our setup is responsible for controlling the different operational stages of the model.

The starting position for the camera is kept during the initial state (home state). When a green ball is detected, the model starts moving the camera to follow the ball (tracking state). As long as this is successful, the algorithm keeps tracking. If the detection fails, the algorithm waits for threeseconds (waiting state) before returning to its starting position (home state). If the ball reappears during the three-second period, the system returns to tracking mode.

A Stateflow diagram showing the algorithm in tracking mode can be seen in Figure 4. Tracking stage, waiting stage, and home stage are clearly visible. Stage transitions are marked with conditions. Possible modifications of this module could include increasing the waiting period or changing the behaviour from returning home to a

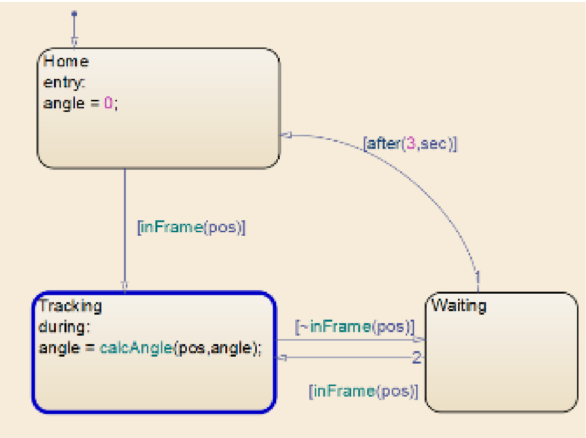


Figure 4: Defining operational states of embedded systems

sweeping search motion if the connection is lost.

3.4 Communicating with other embedded systems

The Raspberry Pi is responsible for image acquisition and object detection. However, the motor that moves the camera is controlled by an Arduino Unoin the presented setup. Communication is established via a LAN. Therefore, IP communication, network settings, and networking topics can be discussed. Possible extension for this module might be wireless LAN or serial communication over USB.

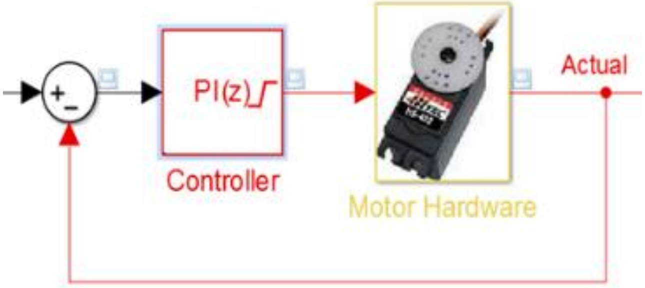


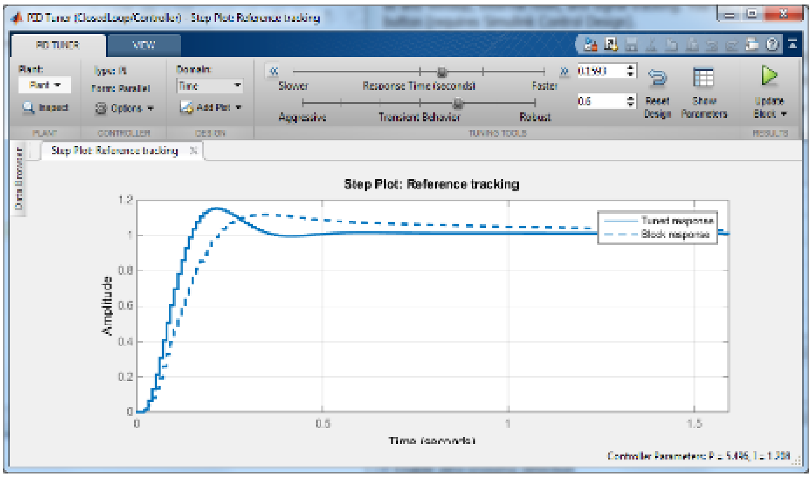
Figure 5: Motor control loop

3.5 Low-level commands for motor control

The next module is run on the Arduino Unoand translates the detected location of the ball into translational commands and further into actual voltage levels for the camera control motor. The motor control loop is depicted in Figure 5.

3.6 Testing and parameter tuning

A crucial part of the development process is the testing and parameter tuning. While the parameters can be modified offline, and even online in External Mode, simulation of the system and measurements of the system parameters can be used to optimize system behaviour as depicted in Figure 6. The effects of parameter changes can be experienced in simulation and in reallife.



Plant: Plant
Type: PI
Form: Parallel
Domain: Time
Controller Parameters: P = 5.496, I = 1.338

Figure 6: Tuning parameter to match plant simulation results and measured data from real motor control system

3.7 Automated code generation and embedded systems

The code for the target platforms is automatically generated from Simulink models. It can be modified and integrated into other environments. Raspberry Pi and Arduino function as fully embedded systems. Both concepts—automated code generation and embedded systems—can be introduced using the setup. Possible modifications could be the substitution of one or both platforms, the integration of external code, or the addition of additional nodes to the system.

4 CONCLUSION AND FUTURE WORK

Thispaper discussed the importance of laboratories for engineering education. Laboratories are a cornerstone of engineering education as postulated by numerous engineering education associations, accreditation bodies, and scientific publications alike.

However, traditional laboratories have drawbacks such as the required investments in preparation, supervision, and hardware and software. Virtual laboratories can be introduced to reduce some of the investments in hardware and software. However, there is reasonable doubt that virtual experiments can substitute real hands-on experiences.

Low-cost hardware is a promising alternative thatallows the reduction of hardware costs. Students can have access to their own hardware to allow them to work with the laboratory hardware anywhere and anytime.

Furthermore, this flexible hardware can be used, much likethe software tool chain, throughout a student’s studies. A single hardware setup can be used as an example to discuss several topics of importance.

We present an example of an embedded system consisting of an Arduino UnoR3 with a motor control board, a Raspberry Pi Model B, and an off-the-shelf webcam. The system is designed to track a green ball with the camera attached to the motor. The models and algorithms offer insight into image acquisition and processing, supervisory control and state logic, motor control, system identification, parameter tuning, prototype testing, embedded systems, and Model-Based Design.

We are currently collecting material and will publish the models, algorithms with their hardware and software requirements,and assembly and use instruction for public access[20, 21].

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