Applying a Common Framework to Develop Undergraduate Control Systems Laboratory Kits

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***Abstract*— In the literature, there are many examples of control systems laboratory experiments and equipment. However, the information provided about these laboratories is not consistent. This paper applies a common framework for control systems laboratories to compare six existing low-cost laboratory kits for control systems and mechatronics. The framework contains learning objectives, components of a laboratory apparatus, and concepts for undergraduate control systems courses. It was developed based on a series of surveys of the control systems community. Additionally, a procedure is provided for how to apply the common framework for new laboratory developments and to improve consistency and ease of comparison of laboratories in the future. Due to diversity and differences between the disciplines that teach control systems, this procedure is provided as a guide rather than a prescriptive set of instructions. While using the procedures, instructors may select from the items on each list of the common framework to develop an effective laboratory experience for their students but are encouraged to explain the rationale for which items were selected when sharing their laboratory experience with other instructors. While previous literature has lacked the consistency of details, the goal of this paper is to show how this common framework can be applied in the future to increase understanding and transferability of control systems laboratories across institutions and disciplines.**

Keywords*— *Control systems, equipment, instructional laboratory, learning objectives, undergraduate

I. INTRODUCTION

In 2015, through surveys of control systems faculty, laboratory instructors, and industry professionals, a common framework to describe undergraduate control systems laboratories was developed. The goal of this framework was to establish a common basis of comparison for existing laboratories, open the door for possible collaboration for laboratory development, and provide common criteria for evaluating new components and experiments. In this paper, six recently developed low-cost control systems laboratories are evaluated based on the common framework and a procedure for developing laboratories using the framework is proposed.

II. BACKGROUND

Laboratory experiments and projects are common components of higher education in STEM. Like other aspects of a course, such as tests and homework, the instructional staff at each university generally develop these experiments and projects. To help instructors develop laboratories, some general guidance and evidence-based practices have been published on engineering laboratories [1], and some disciplines like physics have more detailed recommendations for laboratory experiences [2]. However, detailed frameworks or guidance are not available across all STEM disciplines.

Both [3] and [4] emphasize the importance of including hands-on experiments and design problems in control systems courses. Control systems lectures can be highly theoretical; well-designed experiments and design problems can help students connect the theory to practice. Laboratory experiences are common in undergraduate control systems courses and some of these experiences have been documented in the literature [5-27]. As control systems is a diverse, multi-disciplinary field, it follows that there are differences in each one of these experiences. However, there are also some common aspects as well. Some common systems include DC motors [5, 10, 17] and a variety of inverted pendulums [5, 8, 14, 22, 23]. Additionally, laboratory kits that are low-cost and portable are becoming more popular for control systems laboratories [10, 12, 14, 16]. While there are many published articles and websites about these laboratory experiences, the information about them varied significantly in detail. Therefore, the Control Systems Laboratory Framework (CSLF) was developed to create a common basis of comparison for laboratory experiences in control systems [28].

A. Laboratory Objectives

Course objectives and learning outcomes form the foundation for the course and laboratory development. Feisel and Rosa [1] stress the importance of designing laboratories based on clearly stated laboratory objectives and that objectives are often not included in the literature on engineering laboratories. They also indicate confusion among faculty about what exactly an objective is. Felder and Brent [29] define objectives and learning outcomes for programs and courses seeking ABET accreditation. In this study, a learning

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objective is defined as an observable student activity that shows what knowledge or skill has been acquired in the laboratory [29]. An outcome was the knowledge or skill that a student was expected to acquire upon completion of the laboratory [29].

B. Laboratory Kits

There seems to be a trend in the literature to move toward low-cost equipment. Most of the laboratory experiences in the last five years include less than $1,000 of hardware per station or group of students [10, 12, 14, 16]. More recently, there also seems to be a trend to develop kits that can be used outside of a traditional laboratory space. The kit trend seems to be driven by the decreasing size and cost of hardware.

A lab kit allows students to take home the laboratory equipment to complete the experiments on their own time [12, 30]. These kits started to become more popular as the cost of the required hardware has decreased [30]. The kits' contents vary based on the objectives of the course and can be assembled by the instructor [14, 30, 31], adapted from an existing kit [12], or purchased as a complete kit such as Lego Mindstorms NXT [24-26]. Some papers have collected student feedback through end of semester surveys; based on this data the kits have been well received by students [6, 14, 27, 30].

C. Control System Laboratory Framework

The control system laboratory framework (CSLF) was derived based on objectives, concepts, and components of a laboratory apparatus that were the highest rated and achieved consensus amongst the survey participants [28]. In this framework, a learning objective is an observable student activity that shows what knowledge or skill has been acquired in the laboratory. The concepts include the theories, topics, controller types, and techniques used to design control systems. A laboratory apparatus contains everything needed to complete a suite of experiments. In general, for a control systems laboratory, the apparatus includes the physical plant, sensors, data acquisition, controller hardware, software, and wires. The most important objectives in the CSLF are:

1. Connect theory to what is implemented and observed in the laboratory
2. Identify differences between models and physical systems
3. Design and verify a controller meets specifications
4. Model and simulate a system
5. Collect and visualize input and output data
6. Implement a controller learned in lecture
7. Identify practical issues that arise with physical systems such as sensor noise, interference, saturation and large gains
8. Tune a controller

The most important concepts from the CSLF are:

1. Block diagram representation of a system
2. Transfer functions
3. Stability
4. Step response
5. Laplace transforms
6. PID Control
7. Maximum overshoot or percent overshoot, rise time, settling time, and steady-state error
8. Damping ratio and undamped natural frequency
9. Closed loop vs. open loop control
10. Bode plot
11. Frequency response
12. Pole/Zero plots
13. Tracking and disturbance rejection

The most important components of a laboratory apparatus are:

1. MathWorks including MATLAB, Simulink, SISO tool, and QUARK
2. Electro-Mechanical systems including servos and motors
3. Mechanical systems including spring-mass-damper, actuators, or hydraulics
4. Tools representative of industry
5. Electrical systems including first and second order circuits
6. Data acquisition
7. Digital and analog I/O
8. Physical lab bench equipment including power supply, function generator, multimeter, oscilloscope, and spectrum analyzer
9. A/D and D/A conversion

The CSLF was proposed after a series of surveys of control system faculty and industry professionals. From the survey results, the most important objectives, concepts, and components were identified from a longer list of items identified by participants for each category [28]. Additionally, the objectives in the CSLF have already been mapped to the ABET EAC Criterion 3 Student Outcomes [28].

Since control systems is a diverse field, the CSLF was designed to be a guide that could be adapted to a specific course, rather than a prescriptive set of requirements. For example, Bode plots and frequency response might be more important to cover in a mechanical engineering course than an electrical engineering course. Typically, frequency response is covered in another electrical engineering course.

The CSLF also provides a basis of comparison for existing laboratory experiences. Using a common language to document and compare laboratory experiences allows laboratory experiences to be more easily adapted for other courses. Being able to start from an existing laboratory experience will save time and money and increase the chances of success for faculty looking to update their courses and laboratories.

III. Purpose

The items in the CSLF were derived from surveys of current faculty and industry practitioners in control systems. One of the proposed purposes of the CSLF is for faculty to be able to compare existing laboratory experiences to identify kits they could adapt for their own course. This paper uses the CSLF to compare six different laboratory kits recently published in the literature. After this study, it can be determined if the CSLF provides a useful basis for comparison and is representative of current practice in laboratory kit development.

IV. Method

First, a literature search of laboratory experiences for control systems and mechatronics was conducted. This search was limited to the last five years of papers presented at American Society for Mechanical Engineering conferences, the American Control Conference, or the American Society for Engineering Education Annual Conference and Exposition. Since the recent trend in control systems seems to be moving toward affordable (take-home) kits and experiments, the papers on more expensive, in-person experiments were excluded from the search. From the remaining papers, six different kits were selected for comparison. These kits were chosen to represent a variety of universities, disciplines, and hardware. Once the six kits were identified, published literature and websites about each kit were reviewed. From the publically available information, the author determined which items of the CSLF the kit fulfilled. Finally, the data was organized into a table for easy comparison between the six kits. Using the table, similarities and differences were identified.

Some of the papers also included information about how the kits were developed. Common practices of development were merged with the CSLF to propose a process for laboratory development going forward.

V. Results of the Application of the Framework

Six recently developed low-cost control system laboratory kits for undergraduates were compared based on the objectives, concepts, and components of the apparatus in the CSLF. The comparison of the six kits based on the CSLF is captured in Table I. Due to the similarity and confusion between Objectives 3, *design and verify a controller meets specifications*, and 8, *tune a controller*, in the original surveys, they were combined for this analysis. Some survey participants thought that these two objectives meant the student had achieved the same thing. The information gathered for this comparison is based only on published literature. If it could be identified that the kit was designed to meet an objective, demonstrate a concept, or use a component, a Yes was placed in Table I. If an objective, concept, or component was not found, a No was placed in Table I. If enough information was not provided to determine if an objective was met or a concept was covered, a question mark was placed in Table I. While the framework was considered to be common among the participating faculty, there are differences in the way these kits are presented in the literature and in implementation. Additional information about each kit is provided in this section.

A. Motor Kit

The kit, described in [5], is designed for experiments to control a DC Motor; see Fig. 1. It uses a Raspberry Pi to implement the controller and collect data. There is also a solderless breadboard for the interface circuitry between the motor, sensors, and Raspberry Pi. The total cost is about $130. It was designed for a required undergraduate control systems course for general engineering majors at the University of Illinois at Urbana-Champaign.

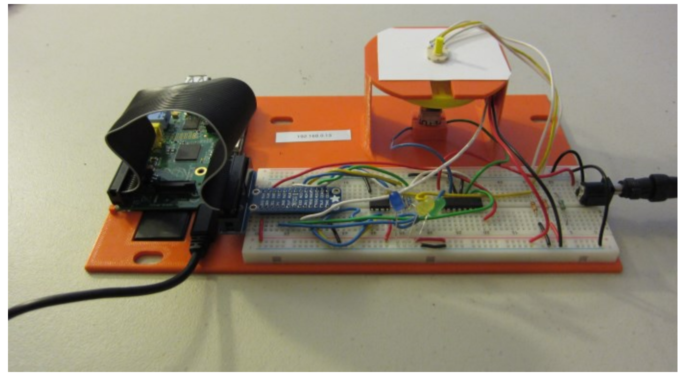

Fig. 1. Motor Kit [5]

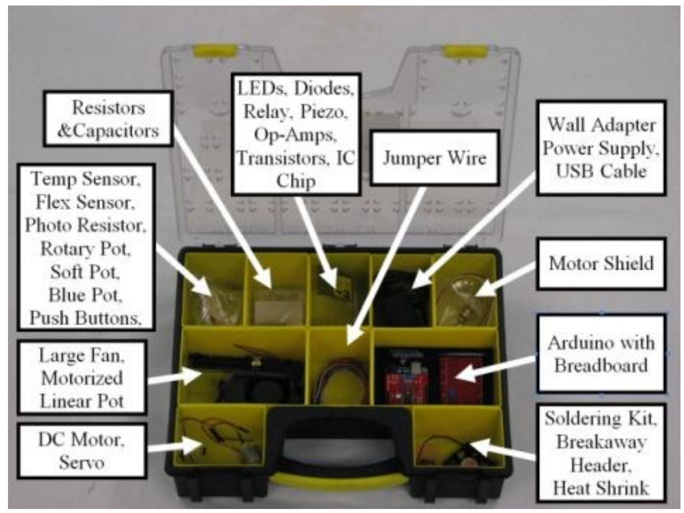

Fig. 2. MESA Box [32]

B. MESA Box

The MESABox [12] is adapted from the Sparkfun Inventor's Kit, an off-the-shelf kit available online; see Fig.2. Some of the included components are an Arduino, ArduMoto shield, a DC motor, and sensors. The total cost is approximately $180. It was used in an introductory control theory course in the mechanical engineering department at the University of California at Merced. In addition to control of a DC motor, a fan is used to control the position of a plate attached to a frame like a pendulum.

C. Hardware Based Variety Kit

In [6], several different hardware based experiments are described. There are six different systems, including RC Circuit, LRC circuit, a pendulum (see Fig. 3), a light bulb, a boost DC-DC converter and a DC motor. These systems were piloted in an introductory dynamic systems and controls course in the mechanical engineering department at the University of Detroit Mercy. All of the systems, plus an Arduino Uno, were designed with a target cost under $150.

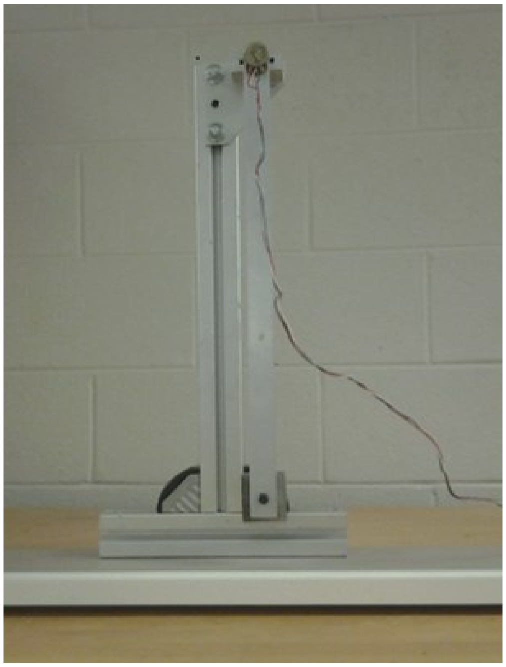

Fig. 3. Pendulum from Hardware variety kit [6]

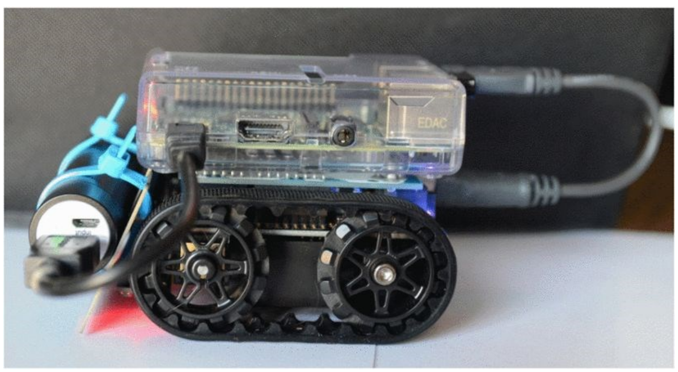

Fig. 4. Line Following Robot [7]

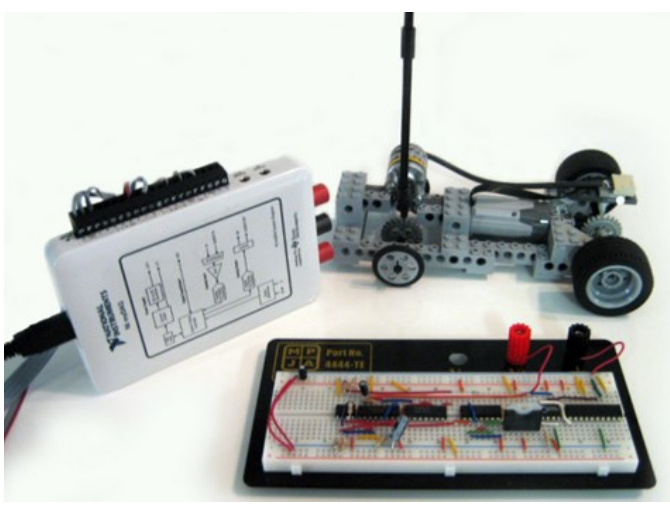

Fig. 5. Science and Engineering Active Learning (SEAL) System [33]

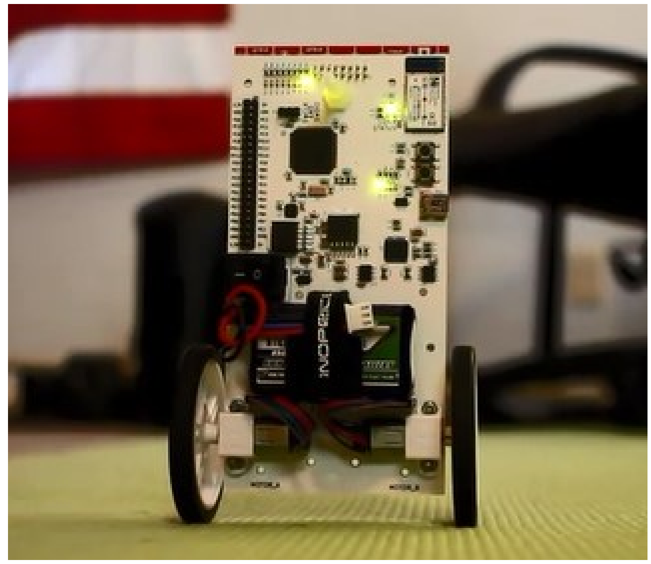

Fig. 6. Eeva Robot [34]

D. Line Following Robot

The robot in [7] is based on an off-the-shelf line-following robot from Pololu Robotics; see Fig. 4. A Raspberry Pi was added to the robot to increase the computing power and capability over just the Arduino that the robot was originally designed with. The complete system costs about $215. In the initial implementation, it was used as a demonstration during a lecture for an introduction to feedback controls course, but it could easily be adapted into a series of laboratory experiments.

E. Science and Engineering Active Learning System

The kit in [14], the science and engineering active learning system (SEAL), is a car with an inverted pendulum attached; see Fig. 5. It was designed for a feedback control systems course in the electrical engineering department at UCLA. The car is built out of Legos, there are interfaces on a protoboard, and a myDAQ from National Instruments is used for data acquisition. The cost of the materials in addition to the myDAQ is approximately $100. The students are able to check out a myDAQ for use during the course.

F. Eeva Robot

Eeva [8] can be used as a SegBot (two-wheeled inverted pendulum robot) or a line-following robot; see Fig 6. The course described uses this robot in a multidisciplinary mechatronics course at Kansas State University. This mechatronics course does not cover traditional control systems topics and control systems is not a prerequisite for the course. While this is a different type of course than others considered in this paper and in the development in the CSLF, the robot described could be adapted for a more traditional control systems course. The robot has two interfaces: driving via an Android app or programming with a Windows user interface.

G. Comparison

Based on Table I, the similarities and differences of each kit can be identified based on the items of the CSLF. The objectives, concepts, and components were compared for each kit.

The concepts were the most difficult to identify from the literature published about these kits. There were 21 question marks in the concepts, which is about 27% of the cells. Only about 5% of the cells in the objectives and 2% of the cells in the components contained question marks. The total number of question marks for each kit ranged from none to seven.

Based on the information in the published literature, none of the kits covered every item on the CSLF. The hardware-based variety kit covered 86% of the items on the CSLF and the motor kit covered 72% of the items. The MESA Box and the line following robot covered the fewest items at 55% and 52% respectively. The Eeva robot and SEAL kit covered 59 % and 62%, respectively.

1) Objectives

The kits had the most similarity in the objectives identified by the CSLF. All six kits were designed for students to achieve four (1, 3, 5, and 7) of the seven objectives. The other three objectives (2, 4, and 6) were designed into five of the six kits. Objective 2 was covered in all of the kits except the line following robot. From the published data it could not be confirmed if Eeva was designed to cover objectives 4 and 6. The other four kits achieved all of the objectives.

TABLE I. CONTROL SYSTEMS LABORATORY KIT COMPARISON WITH COMMON FRAMEWORK

	Motor Kit [5]	MESA Box [12]	Hardware-based Variety [6]	Line Following Robot [7]	SEAL [14]	Eeva [8]
Objectives						
1. Connect theory to what is implemented and observed in the laboratory	Yes	Yes	Yes	Yes	Yes	Yes
2. Identify differences between models and physical systems	Yes	Yes	Yes	No	Yes	Yes
3. Design and verify a controller meets specifications (Tune a controller)	Yes	Yes	Yes	Yes	Yes	Yes
4. Model and simulate a system	Yes	Yes	Yes	Yes	Yes	?
5. Collect and visualize input and output data	Yes	Yes	Yes	Yes	Yes	Yes
6. Implement a controller learned in lecture	Yes	Yes	Yes	Yes	Yes	?
7. Identify practical issues that arise with physical systems	Yes	Yes	Yes	Yes	Yes	Yes
Concepts						
1. Block diagram representation of a system	Yes	Yes	?	?	?	Yes
2. Transfer functions	Yes	Yes	Yes	?	?	Yes
3. Stability	No	No	Yes	?	?	Yes
4. Step response	Yes	?	Yes	?	Yes	Yes
5. Laplace transforms	Yes	?	?	?	Yes	Yes
6. PID Control	Yes	Yes	Yes	Yes	Yes	Yes
7. Maximum overshoot or percent overshoot, rise time, settling time, and steady-state error	Yes	?	?	Yes	?	Yes
8. Damping ratio and undamped natural frequency	No	No	Yes	?	?	?
9. Closed loop vs. open loop control	No	Yes	Yes	Yes	?	Yes
10. Bode plot	Yes	No	Yes	No	Yes	No
11. Frequency response	Yes	No	Yes	No	Yes	No
12. Pole/Zero plots	No	No	Yes	No	Yes	?
13. Tracking and disturbance rejection	No	No	Yes	Yes	?	Yes
Components of a Laboratory Apparatus						
1. MathWorks including MATLAB, Simulink, SISO Tool, and QUARK	Yes	Yes	Yes	No	No	No
2. Electro-Mechanical systems including servos or motors	Yes	Yes	Yes	Yes	Yes	Yes
3. Mechanical systems including spring-mass-damper, actuators, or hydraulics	No	No	Yes	No	No	No
4. Tools representative of industry	Yes	Yes	Yes	Yes	Yes	Yes
5. Electrical systems including first and second order circuits	No	No	Yes	No	No	No
6. Data acquisition	Yes	Yes	Yes	Yes	Yes	Yes
7. Digital and analog I/O	Yes	Yes	Yes	Yes	Yes	No
8. Physical lab bench equipment	No	No	No	No	No	No
9. A/D and D/A conversion	Yes	?	Yes	Yes	Yes	No

2) Concepts

The concepts of the CSLF highlighted the most differences between the six kits. All six kits only had one concept in common, *PID control* (6). In contrast, the hardware-based variety kit was the only kit to demonstrate one concept, *damping ratio and undamped natural frequency (8*). Four of the kits demonstrated an additional three concepts (2, 4, and 9). Half of the kits demonstrated another six concepts (1, 5, 7, 10, 11, and 13). Only two kits demonstrated the remaining two concepts (3 and 12).

None of the kits covered all of the concepts. The coverage ranged from 31% (the MESA Box and the line following robot) to 77% (the hardware-based variety kit).

3) Components of a laboratory apparatus

All of the kits used three of the components of a laboratory apparatus. They all controlled an *electro-mechanical system* (2). Additionally, all of the kits used *tools representative of industry* (4) and had *data acquisition* (6). In contrast, none of the kits used traditional *physical lab bench equipment* (8). The SEAL kit uses a myDAQ, which is the closest to physical lab bench equipment of any of the kits. Other kits, like the motor kit used virtual lab bench equipment such as an oscilloscope. All of the kits, except the Eeva robot, used both *digital and analog I/O* (7). Four of the kits used *A/D and D/A conversion* (9), but the Eeva robot did not and the MESA box was not clear about the conversion of signals. Half of the kits (motor kit, MESA box, and the hardware-based variety kit) used MathWorks software. The hardware-based variety kit was the only kit to use *electrical* (5) and *mechanical* (3) systems in addition to an electro-mechanical system.

VI. Discussion

The comparison in the previous section highlighted both similarities and differences in these six kits. While at least one of the kits included most of the items in the CSLF, none of them incorporated all of the items in the CSLF. Component 8, *physical lab bench equipment* was the only item not incorporated in any of the kits. The omission of this equipment was probably due to each of these examples being designed as kits that can be used outside of a traditional laboratory setting.

The similarities highlighted in this comparison also affirm the applicability of the CSLF to control systems laboratories across disciplines and universities. The comparison also highlights some of the differences between kits, which is also a useful purpose for the CSLF. The comparison could also help faculty adapt existing kits for their own courses and laboratory experiences.

The *objectives* were the most common between the kits. The objectives also achieved the most consensus in the original surveys as well [28]. All six kits met four of the seven objectives. The similarity was not a surprise since most of the objectives are broadly applicable to all control systems laboratories.

The most ambiguity was in the *concepts* covered with each kit. Some authors included more explicit details about the concepts covered than other authors did. Additionally, the difference in course focus might have also led to the differences in concepts covered. The kits compared in this paper cover general engineering, mechanical engineering, electrical engineering, and mechatronics courses, so the emphasis of each course along with any prerequisite courses are different. These differences could explain the differences identified in this comparison. The surveys used to develop the CSLF also found that the emphasis of some concepts varied by discipline (e.g. electrical engineering, mechanical engineering) and level of the course [28].

Most of the differences were in the *components of the laboratory apparatus* used in each kit. The components also had the least amount of consensus in the surveys that were used to develop the CSLF [28]. Since the objectives were similar for all six kits, the difference in components means that there is more than one way to achieve the objectives. The difference in components is not surprising either since there is a similar variety of control system platforms in the industry.

VII. Applying the Framework to New Laboratories

The stated goal of the framework was to create a common language and basis of comparison for control systems laboratories. If a faculty member wanted to develop a laboratory experience from scratch, the following procedure is suggested:

1. Identify *objectives* for the laboratory that closely align with and reinforce the lecture component of the course. The list of objectives in the CSLF is a starting point for this step.
2. Select *concepts* that relate to the lecture and laboratory objectives. The CSLF provides a list of concepts as well, however, the concepts in the laboratory experience should be closely related to the lecture.
3. Set a budget (space, time, and monetary).
4. Pick *components of a laboratory apparatus* that allow students to meet the objectives, demonstrate concepts and fit into the budget. The CSLF can also provide ideas for this step.
5. Create experiments that will meet the objectives and demonstrate the concepts.
6. Implement the laboratory experience in a course
7. Assess the student outcomes via laboratory reports, quizzes, and/or surveys.
8. Adjust and update as needed to ensure that students are achieving the objectives of the laboratory.

The procedure is also illustrated in Fig. 7. As illustrated, steps 3 and 4 can be done in parallel with step 2. As with all course and laboratory development adjusting and improving the experience over time is also important.

It is not proposed that all control systems laboratories should become identical, but rather that framework will guide the development of laboratory experiences that will be adapted to meet the needs of the students in a particular course. For

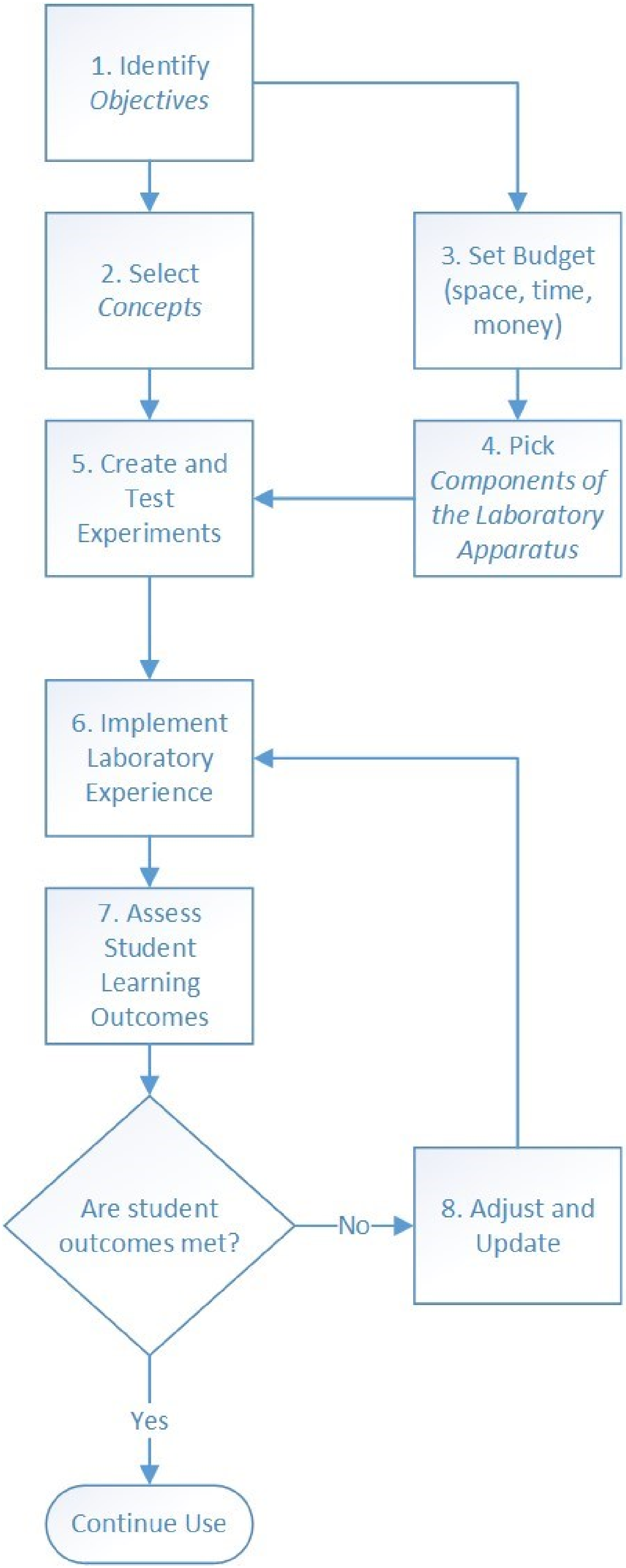

Fig. 7. Development Process using CSLF

example, some courses may choose not to use a PID controller or use the Z-domain rather than the Laplace domain. It also may not be feasible or desirable to achieve all eight objectives with one kit or within one course. The goal of the CSLF would be for future literature and documentation of control systems laboratories would indicate which items of the CSLF the laboratory meets and how it deviated.

VIII. Conclusions and Future Work

In this paper, we have shown how to use the CSLF to compare laboratory kits. While this comparison shows a lot of similarities, these similarities were not readily apparent after brief reading of the respective papers. There are also differences that are highlighted in the comparison. Since the CSLF provided a useful basis of comparison, a procedure for developing and documenting new laboratories with the CSLF was provided.

Future work includes expanding the comparison to other types of laboratory equipment and experiences. In addition, a website is planned that uses the CSLF to compare equipment as it is developed. Finally, expanding the CSLF to include lectures, projects, and blended courses is also being considered.

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